PB86-159845

Environmental Assessment of a Watertube Boiler Firing a Coal-Water Slurry Volume 1. Technical Results

Acurex Corp., Mountain View, CA

Prepared for

Environmental Protection Agency
Research Triangle Park, NC

Feb 86

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-159845

EPA/600/7-86/004a
February 1986

ENVIRONMENTAL ASSESSMENT OF A WATERTUBE BOILER FIRING A COAL-WATER SLURRY

Volume I
Technical Results

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EPA Contract No. 68-02-3188

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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.
EPA/600/7-86/004a		PB86-159845/AS

4. TITLE AND SUBTITLE	5. REPORT DATE
Environmental Assessment of a Watertube Boiler Firing a Coal/Water Slurry; Volume I. Technical Results	February 1986
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
R. DeRosier and L.R. Waterland	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Acurex Corporation P.O. Box 7555 Mountain View, California 94039	11. CONTRACT/GRANT NO. 68-02-3188
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
EPA, Office of Research and Development Air and Energy Engineering Research Laboratory Research Triangle Park, NC 27711	Final; 1/84 - 3/85 14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES AEERL project officer is Robert E. Hall, Mail Drop 65, 919/541-2477. Volume II is a data supplement.

16. ABSTRACT The report describes results from field testing a watertube industrial boiler firing a coal/water slurry (CWS) containing about 60% coal. Emission measurements included continuous monitoring of flue gas emissions; source assessment sampling system (SASS) sampling of the flue gas, with subsequent analysis of samples to obtain total flue gas organics in two boiling point ranges, compound category information within these ranges, specific quantitation of the semivolatile organic priority pollutants, and flue gas concentrations of 73 trace elements; EPA Methods 5/8 sampling for particulate, SO2, and SO3 emissions; and grab sampling of fuel and ash for inorganic composition. NOx, SO2, CO, and TUHC emissions were in the 230-310, 880-960, 170-200, and 1-3 ppm ranges (corrected to 3% O2), respectively, over the two tests performed. Particulate levels at the boiler outlet (upstream of the unit's baghouse) were 7.3 g/dscm in the comprehensive test. Coarse particulate (>3 micrometers) predominated. Total organic emissions were almost 50 mg/dscm, with about 70% of the organic matter in the nonvolatile (>300 C) boiling point range. The bottom ash organic content was 8 mg/g, 80% of which was in the nonvolatile range. Of the PAHs, only naphthalene was detected in the flue gas particulate, with emission levels of 8.6 micrograms/dscm. Several PAHs were found in the bottom ash.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution	Pollution Control	13B
Water Tube Boilers	Stationary Sources	13A
Slurries	Industrial Boilers	11G
Coal	Environmental Assessment	08G, 21D
Assessments		14B

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
Release to Public	Unclassified	92
	20. SECURITY CLASS (This page)	22. PRICE
	Unclassified	

EPA Form 2220-1 (9-73)

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ACKNOWLEDGEMENT

This test program was performed in cooperation with the Pittsburgh Energy Technology Center (PETC). The help and cooperation of Y. S. Pan, D. Snedden, G. Bellas, D. Wildman, and D. Wieczenski of PETC is greatly appreciated. Special recognition is also extended to the Acurex field test team of M. Chips, M. Murtiff, R. Klug, and P. Kaufmann, under the supervision of B. DaRos.

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SECTION 1

INTRODUCTION

This report describes and presents results of environmental assessment tests performed for the Air and Energy Engineering Research Laboratory (AEERL) of EPA under the Combustion Modification Environmental Assessment (CMEA) program, EPA Contract No. 68-02-3188. The CMEA started in 1976 with a 3-year study, the NO_x Control Technology Environmental Assessment (NO_x EA, EPA Contract No. 68-02-2160), having the following four objectives:

- Identify potential multimedia environmental effects of stationary combustion sources and combustion modification technology
- Develop and document control application guidelines to minimize these effects
- Identify stationary source and combustion modification R&D priorities
- Disseminate program results to intended users

During the first year of the NO_x EA, data for the environmental assessment were compiled and methodologies were developed. Furthermore, priorities for the schedule and level of effort for the various source/fuel/control combinations were identified. This effort revealed major data gaps, particularly for noncriteria pollutants (organic emissions and trace elements) for virtually all combinations of stationary combustion

sources and combustion modification techniques. Consequently, a series of seven environmental field test programs was undertaken to fill these data gaps. The results of these tests are documented in seven individual reports (References 1-1 through 1-7) and in the NO_x EA final report summarizing the entire 3-year effort (Reference 1-8).

The current CMEA program has, as major objectives, the continuation of multimedia environmental field tests initiated in the original NO_x EA program. These new tests, using standardized Level 1 sampling and analytical procedures (Reference 1-9) are aimed at filling the remaining data gaps and addressing the following priority needs:

- Advanced NO_x controls
- Alternate fuels
- Secondary sources
- EPA program data needs
  - -- Residential oil combustion
  - -- Wood firing in residential, commercial, and industrial sources
  - -- High interest emissions determination (e.g., listed and candidate hazardous air pollutant species)
- Nonsteady-state operations

Coal-water slurries (CWS) have received attention in recent years as an alternative to oil fuels. CWS has the advantage of allowing certain oil-fired boilers to eliminate their oil requirements without completely redesigning the boiler. Thus, CWS has the potential for application as a near-term technology for conversion of certain oil-burning facilities to coal firing and thereby offsetting high oil prices and frequently uncertain supply situations.

In response to the need for environmental data on burning CWS, as well as other coal-liquid mixtures such as coal-oil-water (COW) and coal-oil mixtures (COM), tests of two COW-fired firetube industrial boilers (References 1-10 and 1-11), a COM-fired watertube boiler (Reference 1-12), and two CWS-fired watertube industrial boilers (this report and Reference 1-13) have been performed. This report presents the results of the emissions assessment of a CWS-fired watertube boiler. The objective of this test was to assess flue gas emissions during typical boiler operating conditions while firing CWS.

Table 1-1 lists all sources tested in the CMEA effort, outlining the combustion modificaton controls implemented and the level of sampling and analysis performed in each case. Results of these test programs are discussed in separate reports.

TABLE 1-1. COMPLETED TESTS DURING THE CURRENT PROGRAM[a]

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Spark-ignited natural-gas-fired reciprocating internal combustion engine	Large bore, 6 cylinder, opposed piston, 186 kW (250 Bhp)/cyl, 900 rpm Model 38TDS8-1/8	-- Baseline (pre-NSPS) -- Increased air-fuel ratio aimed at meeting proposed NO_x NSPS of 700 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Compression ignition diesel-fired reciprocating internal combustion engine	Large bore, 6 cylinder opposed piston, 261 kW (350 Bhp)/cyl, 900 rpm Model 38TDD8-1/8	-- Baseline (pre-NSPS) -- Fuel injection retard aimed at meeting proposed NO_x NSPS of 600 ppm corrected to 15 percent O_2 and standard atmospheric conditions	Engine exhaust: -- SASS -- Method 8 -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Lube oil	Fairbanks Morse Division of Colt Industries
Low-NO_x residential condensing heating system furnished by Karlsons Blueburner Systems Ltd. of Canada	Residential hot water heater equipped with M.A.N. low-NO_x burner, 0.55 ml/s (0.5 gal/hr) firing capacity, condensing flue gas	Low-NO_x burner design by M.A.N.	Furnace exhaust: -- SASS -- Method 8 -- Method 5 -- Gas grab (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel Waste water	New test
Rocketdyne/EPA low-NO_x residential forced-warm-air furnace	Residential warm-air furnace with modified high-pressure burner and firebox, 0.83 ml/s (0.75 gal/hr) firing capacity	Low-NO_x burner design and integrated furnace system	Furnace exhaust: -- SASS -- Method 8 -- Controlled condensation -- Method 5 -- Gas sample (C_1-C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2, CH_4, TUHC Fuel	New test

(continued)

TABLE 1-1. (Continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Pulverized-coal-fired utility boiler, Conesville station	400-MW tangentially fired; new NSPS design aimed at meeting 301 ng/J NO_x limit	ESP inlet and outlet - one test	ESP inlet and outlet -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1 - C_6 HC) -- Continuous NO, NO_x, CO, CO_2, O_2 Coal Bottom ash ESP ash	Exxon Research and Engineering (ER&E) conducting corrosion tests
Nova Scotia Technical College industrial boiler	1.14 kg/s steam (9,000 lb/hr)fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with limestone injection	Boiler outlet -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, CO, CO_2, NO_x Fuel	Envirocon performed particulate and sulfur emission tests
Adelphi University industrial boiler	1.89 kg/s steam (15,000 lb/hr) hot water firetube fired with a mixture of coal-oil-water (COW)	-- Baseline (COW) -- Controlled SO_2 emissions with soda ash (Na_2CO_3) injection	Boiler outlet -- SASS -- Method 5 -- Method 8 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, CO_2, NO_x, SO_2, CO Fuel	Adelphi University
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-oil (COM)	-- Baseline test only with COM	Boiler outlet -- SASS -- Method 5 -- Controlled condensation -- N_2O grab sample -- Continuous O_2, CO_2, NO_x, CO, TUHC Fuel	PETC and General Electric (GE)

(continued)

TABLE 1-1. (Continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
TOSCO Refinery vertical crude oil heater	2.54 Ml/day (16,000 bbl/day) natural draft process heater burning oil/refinery gas	-- Baseline -- Staged combustion using air injection lances	Heater outlet -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous O_2, NO_x, CO, CO_2, HC Fuel oil Refinery gas	KVB coordinating the staged combustion operation and continuous emission monitoring
Mohawk-Getty Oil industrial boiler	8.21 kg/s steam (65,000 lb/hr) watertube burning mixture of refinrey gas and residual oil	-- Baseline -- Ammonia injection using the noncatalytic Thermal DeNO$_x$ process	Economizer outlet -- SASS -- Method 5, 17 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Ammonia emissions -- N_2O grab sample -- Continuous O_2, NO_x, CO, CO_2 Fuels (refinery gas and residual oil)	Mohawk-Getty Oil
Industrial boiler	2.52 kg/s steam (20,000 lb/hr) watertube burning wood waste	-- Baseline (dry wood) -- Green wood	Boiler outlet -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO Fuel Flyash	North Carolina Department of Natural Resources, EPA IERL-RTP
Industrial boiler	3.16 kg/s steam (29,000 lb/hr) firetube with refractory firebox burning wood waste	-- Baseline (dry wood)	Outlet of cyclone particulate collector -- SASS -- Method 5 -- Controlled condensation -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO Fuel Bottom ash	North Carolina Department of Natural Resources, EPA IERL-RTP

(continued)

TABLE 1-1. (Continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Enhanced oil recovery steam generator	15-MW (50 million Btu/hr) steam generator burning crude oil equipped with MHI low-NO_x burner	-- Performance mapping -- Low-NO_x operation	Steamer outlet: -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO, CO_2 -- N_2O grab sample Fuel	Getty Oil Company, CE-Natco
Pittsburgh Energy Technology Center (PETC) industrial boiler	3.03 kg/s steam (24,000 lb/hr) watertube fired with a mixture of coal-water (CWM)	-- Baseline test only with CWM	Boiler outlet: -- SASS -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Collector hopper ash	PETC and General Electric
Spark-ignited, natural gas-fired reciprocating internal combustion engine -- nonselective NO_x reduction catalyst	610-kW (818-hp) Waukesha rich-burn engine equipped with DuPont NSCR system	-- Low NO_x (with catalyst) -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, NO_x TUHC Lube oil	Southern California Gas Company
Industrial boiler	180 kg/hr steam (400 lb/hr) stoker, fired with a mixture of coal and waste plastic beverage containers	-- Baseline (coal) -- Coal and plastic waste	Boiler outlet -- SASS -- VOST -- Method 5 -- Method 8 -- HCl -- Continuous O_2, NO_x, CO, CO_2, TUHC -- N_2O grab sample Fuel Bottom ash Cyclone ash	Vermont Agency of Environmental Conservation

(continued)

TABLE 1-1. (Continued)

Source	Description	Test points unit operation	Sampling protocol	Test collaborator
Industrial boiler	7.6 kg/s steam (60,000 lb/hr) watertube retrofit for coal water mixture firing	-- Baseline test with CWS -- 30-day emissions monitoring	Boiler outlet -- SASS -- VOST -- Method 5 -- Method 8 -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, TUHC, SO_2 Fuel	EPRI, DuPont
Enhanced oil recovery steam generator	15-MW (50 million Btu/hr) steam generator burning crude oil, equipped with the EPA/EER low-NO_x burner	-- Low NO_x (with burner) -- 30-day emissions monitoring	Steamer outlet -- SASS -- VOST -- Method 5 -- Method 8 -- Controlled condensation -- Anderson impactor -- Gas sample (C_1-C_6 HC) -- N_2O grab sample -- Continuous NO_x, CO, CO_2, O_2, SO_2 Fuel	Chevron U.S.A., EERC
Spark-ignited natural-gas-fired reciprocating internal combustion engine -- selective NO_x reduction catalyst	1,490-kW (2,000-hp) Ingersoll-Rand lean-burn engine equipped with Englehard SCR system	-- Low NO_x (with catalyst) -- 15-day emissions monitoring	Catalyst inlet and outlet -- SASS -- VOST -- NH_3 -- HCN -- N_2O grab sample -- Continuous O_2, CO_2, CO, NO, NO_x, NO_x+NH_3 Lube oil	Southern California Gas Company

[a]Acronymns used in the table: EERC, The Energy and Environmental Research Corporation; EPA IERL-RTP, The Environmental Protection Agency's Industrial Environmental Research Laboratory -- Research Triangle Park; EPRI, The Electric Power Research Institute; HC, hydrocarbons; NSCR, nonselective catalytic reduction; NSPS, new source performance standard; SASS, source assessment sampling system; SCR, selective catalytic reduction; TUHC, total unburned hydrocarbon; VOST, volatile organic sampling train

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SECTION 2

TEST FACILITY DESCRIPTION

The Department of Energy's Pittsburgh Energy Technology Center (PETC) combustion test facility consists of a 3.0 kg/s steam (24,000 lb/hr) watertube boiler, an air-cooled steam condenser and deaerator, CWS preparation and storage facilities, and pollution control devices. Figure 2-1 presents a flow diagram of the test facility. The boiler is a package, two-drum, "D"-type watertube boiler with the specifications listed in Table 2-1. The boiler was originally designed by Nebraska Boiler Company to fire No. 6 fuel oil. The furnace section has a flat integral water-cooled floor, ceiling, side walls, and target wall. The burner wall is comprised of 13-cm (5-in.) thick interlocking tongue and groove refractory tile laid in high temperature bonding mortar. The convection section incorporates a Boyer type VH valve-in-head soot blower. This is a standard design normally incorporated in the boiler by the manufacturer for firing no. 6 fuel oil. It has kept the convective section free of ash buildup during all previous combustion tests performed in the unit.

The coal-water slurry (CWS) fired in these tests was prepared in a 6,800 l (1,800 gal) steam-jacketed mix tank which incorporated an agitator comprised of two sets of turbine blades. A predetermined amount of water was charged to the tank before pulverized coal was added through a vertical gravimetric coal feeder at 910 kg/hr (2,000 lb/hr). The CWS was then

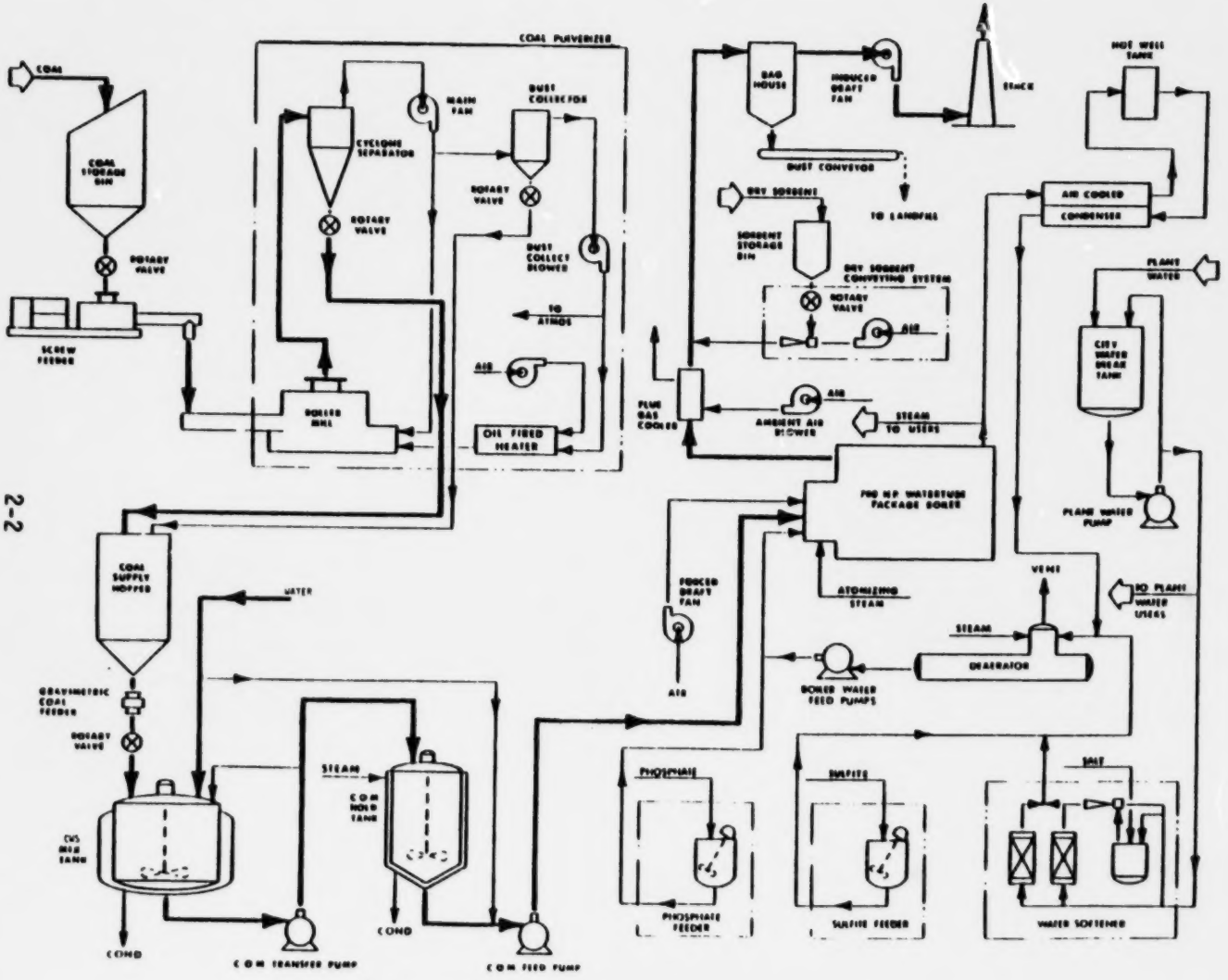


Figure 2-1. PETC combustion test facility flow diagram.

TABLE 2-1. BOILER SPECIFICATIONS

Convection heating surface, m^2 (ft^2)	182 (1,956)
Radiant heating surface, m^2 (ft^2)	48 (518)
Furnace dimensions, m (ft)	1.92 x 4.05 x 2.26 (6.3 x 13.3 x 7.4)
Design steam capacity, kg/s (lb/hr)	3.0 (24,000)
Design pressure, MPa (psig)	1.7 (250)
Operating pressure, MPa (psig)	1.2 (175)
Soot blower	One Boyer-type VH valve-in-head
Year installed	1978

transferred to a 10,600 l (2,800-gal) hold tank incorporating an agitator with one set of turbine blades. The CWS was recirculated from the bottom to the top of the tank by a Viking rotary pump.

The fuel was driven by a variable speed CWS feed pump through flow meters and fuel preheaters before reaching the burner. The CWS flowrate was regulated by the adjustable-speed-drive motor driving the progressive cavity Moyno pump. A Micro-Motion mass flow meter and a Floco positive displacement meter measured the mass and volume flowrates.

A packaged, single-burner Model Fyr-Compak, manufactured by the Coen Company, comprised the firing equipment. The original Coen Model no. 2mV, inside-mix, steam-atomized burners were replaced with slightly different

no. 2mV burners modified for abrasive service. The changes consisted of an optional pintle in the burner body, to reduce carbon buildup inside the burner cap, and the substitution of 440C case-hardened steel as the construction material.

The four valves originally installed in the fuel train were removed or replaced to avoid clogging with coal particles. The oil pressure differential regulator and oil flow control valve were removed and the variable speed drive CWS feed pump was used to control the fuel flowrate. The safety shutoff solenoid valve and the oil return solenoid valve were replaced by pneumatically actuated stainless steel full-ported ball valves. The packaged burner incorporated an automatic air register louver control that closed in on the register louvers at low fire to maintain air velocity and swirl. Combustion air was supplied by a forced-draft fan.

SECTION 3

EMISSION RESULTS

The objective of this test program was to measure flue gas emissions from the boiler during typical operation while burning a coal-water slurry (CWS). This section describes the test arrangement and presents emissions results. Section 3.1 summarizes boiler operating conditions. Sections 3.2 through 3.5 summarize emission results by pollutant grouping; criteria and other gas phase emissions are discussed in Section 3.2, trace elements in Section 3.3, and organic species emissions in Section 3.4. Section 4 discusses the potential environmental significance of emissions measured and presents results of biological testing of samples collected.

3.1 BOILER OPERATION AND TEST ARRANGEMENTS

The sampling matrix called for in the test plan consisted of the following:

- Fuel grab sample
- Bottom ash grab sample
- Baghouse ash grab sample
- Flue gas:
  - -- Continuous monitors for O_2, CO_2, NO_x, CO, SO_2, and total unburned hydrocarbons (TUHC)
  - -- Source Assessment Sampling System (SASS) sampling

-- Combined EPA Method 5/8 sampling for particulate and sulfur species emissions

-- Gas grab sampling for onsite measurement of C_1 to C_6 hydrocarbon emissions

-- Gas grab sampling for laboratory N_2O analysis

All flue gas sampling was performed at the boiler outlet, upstream of the facility's particulate control device (baghouse). Details of the specific sampling protocols used are given in Appendix A.

Two separate tests were performed on the unit. During the first test, performed with a CWS fuel containing 60.9 percent (weight) coal, difficulties were experienced with the SASS sampling equipment. As a consequence, a complete set of test data was not obtained for this test. Specifically, SASS train samples were not collected in this first test. Therefore a second set of tests, performed with the unit firing a CWS fuel containing 58.9 percent coal, was subsequently performed. A complete set of test data was obtained during the second test.

Table 3-1 summarizes the boiler operating conditions for both tests performed. As noted, conditions for both tests were similar, although the second test was run at lower excess air level.

Table 3-2 summarizes the fuel analysis results for both tests. Results supplied for the parent coal by PETC as well as those obtained by independent analyses of the test 2 fuel through this study are both shown.

The independent CWS compositions for the test 2 fuel (measured in this study and calculated based on the coal ultimate analysis reported by PETC and the CWS proportions of water and additive) were generally similar, although the water content of the fuel in this study's analysis was lower

TABLE 3-1. BOILER OPERATING CONDITIONS

	Test 1	Test 2
Steam flow, kg/s (lb/hr)	3.03 (24,000)	3.03 (24,000)
Drum pressure, MPa (psi)	1.3 (189)	1.3 (189)
Furnace draft, Pa (in. H_2O)	112 (0.47)	116 (0.466)
Fuel flow, kg/s (lb/min)	0.410 (54.2)	0.39 (51.8)
Steam temperature, °C (°F)	186 (367)	188 (371)
Boiler feedwater temperature, °C (°F)	101 (213)	--[a] --
Combustion air temperature, °C (°F)	24 (76)	28 (83)
Flue gas temperature °C furnace exit, (°F)	272 (522)	291 (556)
Excess air percent[b]	14	11

[a]Not available
[b]Calculated from PETC fuel composition and flue gas O_2 levels

TABLE 3-2. FUEL ANALYSES (PERCENT BY WEIGHT)

	Coal (dry basis) PETC[a]	CWS (as fired) Test 1 PETC[b]	CWS (as fired) Test 2 This study[a]	CWS (as fired) Test 2 PETC[b]
Carbon	82.23	50.08	47.90	48.43
Hydrogen	5.60	3.41	3.34	3.30
Oxygen (by difference)	6.76	4.12	8.56	3.98
Nitrogen	1.60	0.97	1.02	0.94
Sulfur	1.19	0.72	0.80	0.70
Ash	2.62	1.60	1.93	1.54
Additive	--	0.50	--	0.50
Water	--	38.60	36.45	40.6
Higher heating value, kJ/kg (Btu/lb)	34,459 (14,829)	20,986 (9,031)	21,341 (9,184)	20,296 (8,734)

[a]Measured
[b]Calculated based on coal ultimate analysis and reported proportion of coal, additive, and water in the CWS formulation

than the proportion as reported by PETC. The fuel composition measured in this study, when available, were used in the calculations reported herein.

3.2 CRITERIA POLLUTANT AND OTHER GAS PHASE EMISSIONS

Table 3-3 summarizes emissions of CO, CO_2, O_2, NO_x, SO_2, TUHC, N_2O, and particulate in the flue gas for the tests. As shown, average NO_x (NO + NO_2) emissions (corrected to 3 percent O_2) with the CWS fuel ranged from an average of 231 ppm in test 1 to 312 ppm in test 2. This difference in NO_x emissions between the two tests is not considered significant. Differences of this magnitude often accompany minor changes in boiler operation or fuel properties. CO and TUHC emissions were also similar for the two tests -- averaging 172 ppm and 1.1 ppm respectively in test 1, and 196 ppm and 2.8 ppm respectively (all corrected to 3 percent O_2) in test 2.

SO_2 emissions measured using the PETC continuous monitor were slightly lower in the second test, averaging 885 ppm, than in the first test, averaging 957 ppm. SO_2 emissions measured by EPA Method 8 were similar (though lower) to the continuous monitor reading for test 2. However, results of the Method 8 tests for test 1 were significantly lower than the monitor reading. Measured SO_3 emissions for both tests were quite low.

Particulate levels in the boiler outlet gas, as measured by EPA Method 5, apparently nearly doubled in test 2 over test 1. It is possible that the higher mass emissions for the second test were due to lower combustion efficiency with higher combustible losses in the flyash. The particulate levels at the boiler outlet for test 2 corresponds to an emission rate over 2.3 times that accountable by the ash content of the fuel (i.e., if all the fuel ash were discharged as flyash). Although the boiler outlet flue gas particulate was not analyzed for carbon content, the baghouse hopper ash

TABLE 3-3. CRITERIA POLLUTANT AND OTHER GAS SPECIES EMISSIONS

Species	Test 1 Range	Test 1 Average	Test 2 Range	Test 2 Average
As measured by continuous gas analyzers				
O_2, percent dry	2.3 to 2.9	2.8	1.9 to 2.7	2.1
CO_2, percent dry	14.6 to 15.2	14.9	15.1 to 15.9	15.7
NO_x[a], ppm	196 to 293	234	255 to 437	327
CO, ppm	130 to 213	174	151 to 358	206
TUHC, ppm	0.03 to 2.6	1.1	2.3 to 5.0	2.9
SO_2, ppm	846 to 1,060	968	888 to 964	931
Grab sample				
N_2O, ppm	29 to 35	31	45 to 110	81
Method 8				
SO_2, ppm	--[b]	310	--[b]	800
SO_3, ppm	--[b]	0.85	--[b]	<0.5

Corrected gaseous emissions	ppm[c]	ng/J[d]	lb/10^6 Btu[d]	ppm[c]	ng/J[d]	lb/10^6 Btu[d]
NO_x[a] (as NO_2)	231	136	0.316	312	172	0.400
CO	172	62	0.14	196	66	0.15
TUHC (as CH_4)	1.1	0.2	0.0005	2.8	0.53	0.00012
SO_2[e]	957	786	1.83	885	680	1.58
N_2O	30	18	0.041	76	41	0.095
SO_2[f]	310	255	0.592	760	582	1.35
SO_3[f]	0.84	0.86	0.002	<0.5	<0.5	<0.001

Solid particulate mass emissions	mg/dscm	ng/J[d]	lb/10^6 Btu[d]	mg/dscm	ng/J[d]	lb/10^6 Btu[d]
Method 5	3,485	1,064	2.47	7,255	1,991	4.63
SASS	--[g]	--[g]	--[g]	6,820	1,872	4.35

[a] NO + NO_2
[b] Extractive sample over test duration; range not applicable
[c] Corrected to 3 percent O_2, dry
[d] Heat input basis
[e] Continuous monitor
[f] Method 8
[g] No SASS test for test 1

was. This ash contained 61.6 percent carbon (dry basis, average of two analyses). The bottom ash was high in carbon content as well, 35.7 percent dry basis. Unfortunately, no sample of the test 1 baghouse ash was analyzed. However, if the carbon content of the test 1 particulate was significantly lower than that for test 2, the difference in measured particulate levels might be explained on this basis. In any case, it bears emphasis that the high (for both tests) particulate levels measured reflect the fact that sampling was performed at the boiler outlet. Levels measured would not be indicative of those downstream of a particulate control device. Table 3-3 also shows quite good (within 6 percent) agreement between the Method 5 (isokinetic traverse) and the SASS (single point) particulate measurement result.

Table 3-4 shows the relative size distribution of the particulate as measured by the SASS train. As shown, well over half the particulate (by weight) was greater than 10 μm, and almost 70 percent greater than 3 μm in diameter.

Three gas grab samples were taken during the first test and four during the second test for N_2O analysis. These averaged 30 ppm and 76 ppm (3 percent O_2, dry) respectively, as shown in Table 3-3.

Analysis results for all seven samples taken are shown plotted versus the corresponding NO_x ($NO + NO_2$) emission level, at the time the samples were taken, in Figure 3-1. (NO_x was measured using a chemiluminescent continuous analyzer; this method does not respond to N_2O.) Data from tests performed on several other fossil-fuel-fired external combustion sources are also shown in the figure. The data show that N_2O emission levels are generally about 20 percent of the corresponding NO_x emission level. In fact,

TABLE 3-4. FLUE GAS PARTICLE SIZE DISTRIBUTION (UNCONTROLLED)

Particle size	Emission rate (g/dscm)	(ng/J)	(percent of total)
>10μm	4.34	1,190	63.6
3 to 10μm	0.38	100	5.6
1 to 3μm	1.19	330	17.4
Filter (<1μm)	0.91	250	13.4
Total	6.82	1,870	100.0

a least squares curve fit of all the data points shown in Figure 3-1, with the constraint that the curve pass through the origin, gives the correlation, $N_2O = 0.22\ NO_x$, with a correlation coefficient (r^2) of 0.88. Data from these tests, shown as solid points in Figure 3-1, support this relationship, shown as the straight line in the figure.

3.3 TRACE ELEMENT ANALYSIS RESULTS

The boiler flue gas SASS train samples, the CWS fuel, and the bottom ash and the baghouse hopper ash samples were analyzed for 73 trace elements using Spark Source Mass Spectrometry (SSMS), supplemented by Atomic Absorption Spectrosocopy (AAS). Analysis results for the fuel, SASS particulate, bottom ash, and baghouse hopper ash are summarized in Table 3-5. The data in the table show that all ash streams noted had generally similar composition for most elements and, in fact, had composition quite similar to the ash

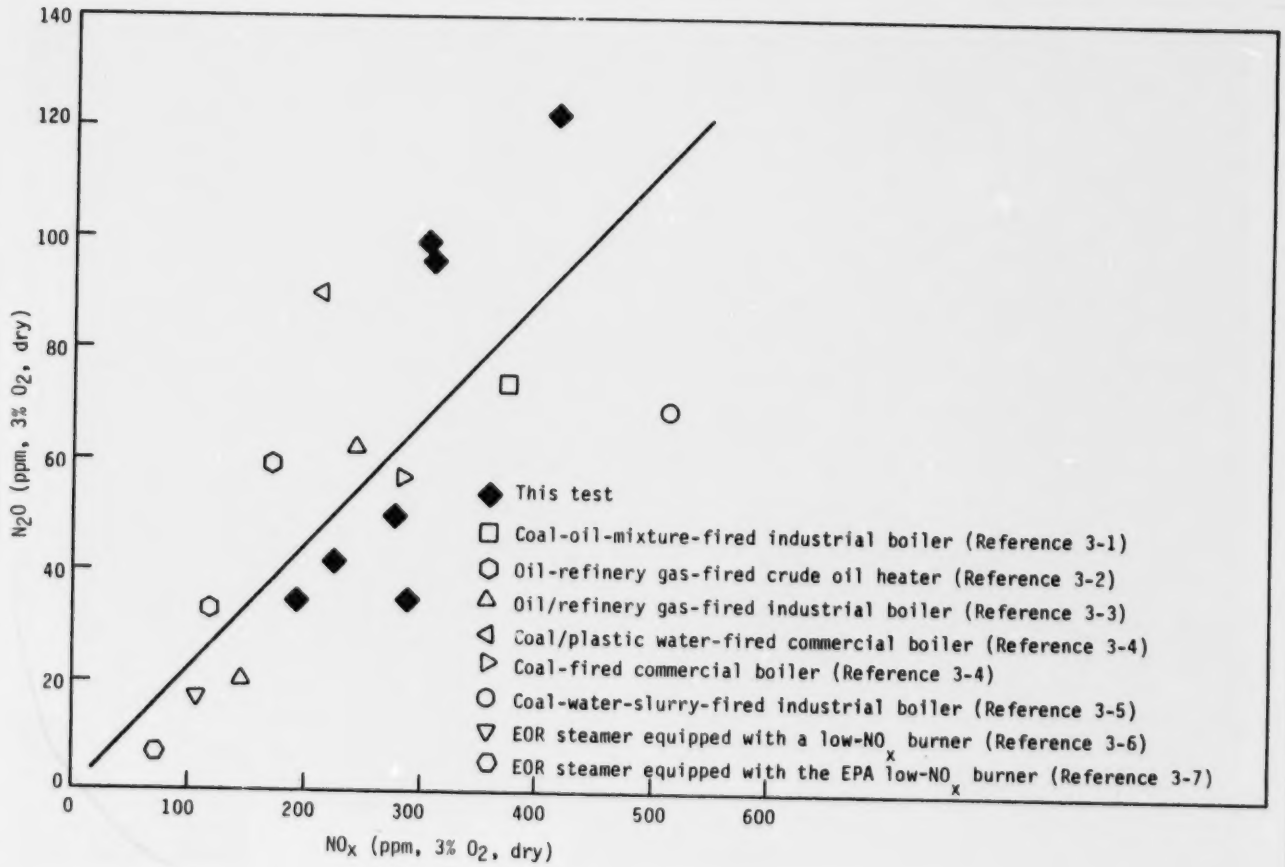


Figure 3-1. N_2O versus NO_x emissions for external combustion sources.

TABLE 3-5. FUEL AND ASH STREAM TRACE ELEMENT ANALYSIS RESULTS

Element	Concentration (µg/g)				
			Flue gas particulate		
	Fuel[a]	Bottom ash	10 + 3 µm	1 µm + filter	Baghouse hopper ash
Aluminum	13,400	60,700	31,300	73,300	43,000
Antimony	0.40	21	11	18	13
Arsenic	1.0	110	30	440	100
Barium	25	1,000	1,000	1,600	1,000
Beryllium	0.40	7.0	8.0	4.0	16
Bismuth	0.03	3.0	--[b]	2.0	0.80
Boron	0.50	54	8.0	120	51
Bromine	1.0	8.0	35	30	85
Cadmium	<0.04	9.0	6.0	30	4.0
Calcium	38,100	14,200	4,400	2,380	8,300
Cerium	1.0	120	85	61	140
Cesium	0.20	1.0	3.0	0.30	2.0
Chlorine	3.0	110	410	8,400	620
Chromium	2.0	620	170	170	230
Colbalt	1.0	21	14	270	190
Copper	3.0	270	110	710	330
Dysprosium	0.10	8.0	9.0	3.0	6.0
Erbium	0.10	4.0	4.0	1.0	3.0
Europium	0.07	1.0	2.0	1.0	4.0
Fluorine	5.0	71	160	180	86
Gadolinium	0.20	5.0	5.0	2.0	7.0
Gallium	2.0	45	15	430	160
Germanium	0.50	5.0	4.0	53	22
Gold	--	--	--	--	--
Hafnium	<0.30	5.0	4.0	0.80	2.0
Holmium	0.10	5.0	6.0	2.0	4.0
Iodine	0.70	4.0	4.0	3.0	5.0
Iridium	--	--	--	--	--
Iron	700	43,500	24,100	40,500	36,100
Lanthanium	2.0	93	75	54	200
Lead	2.0	5,200	150	77	450
Lithium	0.70	38	25	74	35
Lutecium	0.01	0.80	2.0	0.60	1.0
Magnesium	>100	2,800	1,200	4,500	1,900
Manganese	2.0	500	92	>530	500

(continued)

[a]Ash content of fuel was 1.93 percent
[b]Double dashes denote less than detection limit, generally 0.1 µg/g

TABLE 3-5. (continued)

Element	Concentration (µg/g)				
	Fuel[a]	Flue gas particulate			
		Bottom ash	10 + 3 µm	1 µm + filter	Baghouse hopper ash
Mercury	--	--	--	--	--
Molybdenum	1.0	57	70	76	28
Neodymium	0.60	23	16	6.0	55
Nickel	2.0	190	30	480	60
Niobium	0.50	35	19	9.0	51
Osmium	--	--	--	--	--
Palladium	--	--	--	--	--
Phosphorus	37	6,000	1,600	2,800	2,300
Platinum	--	--	--	--	--
Potassium	10,300	5,000	2,100	4,500	2,500
Praesodymium	0.30	11	21	6.0	51
Rhenium	--	--	--	--	--
Rhodium	--	--	--	--	--
Rubidium	0.20	39	39	18	21
Ruthenium	--	--	--	--	--
Samarium	0.30	9.0	17	5.0	21
Scandium	0.30	47	11	61	32
Selenium	0.30	11	15	29	44
Silicon	69,200	104,000	60,600	124,000	63,000
Silver	0.20	<3.0	<0.60	4.0	<2.0
Sodium	100	13,300	8,200	34,600	11,600
Strontium	34	300	1,000	300	300
Sulfur	8,000	5,500	5,500	5,200	5,500
Tantalum	0.10	8.0	15	4.0	100
Tellurium	0.20	1.0	1.0	0.40	0.60
Terbium	0.06	2.0	3.0	0.60	2.0
Thallium	0.20	7.0	--	6.0	3.0
Thorium	0.50	22	31	9.0	42
Thulium	<0.02	0.20	0.30	0.40	0.30
Tin	0.04	41	1.0	6.0	9.0
Titanium	63	2,500	2,500	4,000	3,000
Tungsten	0.10	9.0	9.0	3.0	12
Uranium	0.50	18	16	8.0	19
Vanadium	3.0	2,000	180	400	2,000
Ytterbium	0.10	4.0	6.0	3.0	6.0

(continued)

[a]Ash content of fuel was 1.93 percent
[b]Double dashes denote less than detection limit, generally 0.1 µg/g

TABLE 3-5. (continued)

Element	Fuel[a]	Concentration (µg/g)			
			Flue gas particulate		
		Bottom ash	10 + 3 µm	1 µm + filter	Baghouse hopper ash
Yttrium	4.0	270	79	120	320
Zinc	2.0	4,600	88	73	160
Zirconium	2.0	130	230	45	160

[a]Ash content of fuel was 1.93 percent
[b]Double dashes denote less than detection limit, generally 0.1 µg/g

residue of the fuel (the fuel levels noted in Table 3-5 divided by the ash content of the fuel -- 1.93 percent).

Given the trace element concentrations as determined by laboratory analysis, trace element flue gas emission concentrations (mg/dscm) and flowrates normalized to heat input (ng/J) were computed. Table 3-6 shows the emission results on these bases. (Elemental mass balances were not computed since bottom ash and baghouse hopper ash flowrates were not measured).

As shown in Table 3-6, the elements silicon, aluminum, iron, sodium, calcium, titanium, potassium, magnesium, and phosphorus were present in concentrations exceeding 10 mg/dscm (2.7 ng/J) in the flue gas. These 10 elements were also found in high concentrations in the fuel, as noted in Table 3-5. Most of the element emission levels noted were associated with the flue gas particulate sample. Recalling that sampling was done at the boiler outlet, the levels noted in Table 3-5 would not reflect those downstream of a particulate control device.

3.4 ORGANIC EMISSIONS

Organic analyses were performed on specified flue gas samples according to EPA Level 1 protocol (Reference 3-8) as outlined in Appendix A. The SASS train particulate, organic module sorbent (XAD-2), and organic module condensate (OMC) samples were extracted with methylene chloride in a Soxhlet apparatus. The extracts (the XAD-2 and OMC extracts were combined) were then subjected to total chromatographable organic (TCO) and gravimetric (GRAV) analyses to determine species within the 100° to 300°C (212° to 572°F), and greater than 300°C (572°F) boiling point ranges, respectively. Infrared (IR) spectra of the GRAV residue of the extracts were also obtained. The XAD-2

TABLE 3-6. TRACE ELEMENT EMISSIONS IN THE FLUE GAS

Element	Emissions (mg/dscm)	Emissions (ng/J)	Element	Emissions (mg/dscm)	Emissions (ng/J)
Aluminum	297,000	82	Neodymium	87	0.024
Antimony	90	0.02	Nickel	1,330	0.37
Arsenic	1,060	0.3	Niobium	107	0.03
Barium	7,950	2	Osmium	--	--
Beryllium	45	0.01	Palladium	--	--
Bismuth	4	0.001	Phosphorus	13,200	3.6
Boron	290	0.08	Platinum	--	--
Bromine	238	0.06	Potassium	19,300	5.3
Cadmium	34	0.009	Praseodymium	113	0.03
Calcium	25,300	6.9	Rhenium	--	--
Cerium	526	0.14	Rhodium	--	--
Cesium	14	0.004	Rubidium	220	0.06
Chlorine	19,600	5.4	Ruthenium	--	--
Chromium	1,190	0.33	Samarium	88	0.02
Cobalt	640	0.17	Scandium	185	0.05
Copper	2,030	0.56	Selenium	167	0.04
Dysprosium	47	0.01	Silicon	537,000	148
Erbium	20	0.006	Silver	9.6	0.003
Europium	11	0.003	Sodium	>111,000	>31
Fluorine	1,300	0.36	Strontium	1,090	0.3
Gadolinium	27	0.007	Sulfur	>37,900	>10.4
Gallium	978	0.27	Tantalum	77	0.02
Germanium	130	0.03	Tellurium	5	0.001
Gold	--	--	Terbium	15	0.004
Hafnium	20	0.005	Thallium	13	0.003
Holmium	32	0.009	Thorium	161	0.04
Iodine	26	0.007	Thulium	2	0.0006
Iridium	--	--	Tin	23	0.006
Iron	201,000	55	Titanium	19,900	5.4
Lanthanum	470	0.13	Tungsten	48	0.01
Lead	850	0.23	Uranium	90	0.02
Lithium	270	0.07	Vanadium	1,670	0.46
Lutetium	10	0.003	Ytterbium	34	0.009
Magnesium	15,000	4.1	Yttrium	618	0.17
Manganese	>1,700	>0.47	Zinc	632	0.17
Mercury	--[a]	--[a]	Zirconium	1,160	0.32
Molybdenum	200	0.05			

[a]Double dashes indicate that emissions were below detection limit

and boiler bottom ash extracts were subjected to further separation by liquid column (LC) chromatography followed by TCO, GRAV, and IR analysis of eluted fractions. Direct insertion probe low resolution mass spectrometry (LRMS) analyses were also performed on selected LC fractions. In addition, volatile organic gas phase species with boiling points in the nominal C_1 to C_6 range -160 to 100°C (-260° to 212°F) were measured by multiple analyses of flue gas samples onsite using gas chromatography. A discussion of the analytical results follows.

3.4.1 Total Organic Analyses

TCO and gravimetric analyses were performed on the SASS train cyclone, filter, XAD-2 sorbent, and organic module condensate (OMC) extracts. The results of these and the onsite GC analyses for C_1 to C_6 hydrocarbons are summarized in Table 3-7. The total concentration of organic matter in the flue gas was 48 mg/dscm. Approximately 70 percent of the organic matter was in the nonvolatile (C_{16}+) boiling point range. Total organic emissions in these tests were over an order of magnitude higher than the range of 0.12 to 4.3 mg/dscm reported for oil- and coal-fired boilers in a report summarizing results of other comprehensive field tests (Reference 3-9). These high emissions are consistent with the poor boiler efficiency and high combustible losses (especially high carbon carryover in the flyash) noted previously.

Table 3-7 also shows the C_1 to C_6 hydrocarbon data obtained during test 1 (the SASS train sampling was not successful for test 1). The test 1 data are quite comparable to those of test 2. Most of the hydrocarbon emitted in this volatile boiling point range was low molecular weight C_1 and C_2 compounds.

TABLE 3-7. SUMMARY OF FLUE GAS TOTAL ORGANIC EMISSIONS

	Test 1		Test 2	
	(mg/dscm)	(ng/J)	(mg/dscm)	(ng/J)
Volatile organics analyzed in the field by gas chromatography				
C_1	3.5	1.07	3.0	0.82
C_2	10.5	3.20	5.9	1.60
C_3	--	--	--	--
C_4	--	--	--	--
C_5	--	--	0.3	0.08
C_6	--	--	--	--
Total C_1 to C_6	14.0	4.27	9.1	2.50
Semivolatile organics analyzed by TCO				
XAD-2 and organic module condensate	--[a]	--[a]	5.9[b]	1.62[b]
Total C_7 to C_{16}			5.9	1.62
Nonvolatile organics analyzed by gravimetry				
10 + 3μm cyclones			0.67	0.18
1μm cyclone + filter			0.45	0.12
XAD-2 and organic module condensate			32.0	8.78
Total C_{16}+	--[a]	--[a]	33.1	9.09
Total organics			48.1	13.2

[a]SASS train sampling not performed for test 1
[b]Average of duplicate analyses

Table 3-8 summarizes the total organic analysis results for the ash stream samples taken. As noted, the organic content of the bottom ash sample was quite high, again consistent with the evident poor combustion efficiency existing during test 2. The relative organic contents of the bottom ash and the baghouse hopper ash was consistent with their relative carbon content (61.0 percent for the bottom ash and 35.7 percent for the baghouse hopper ash).

3.4.2 Infrared (IR) Spectra of Total Extracts

The results of the IR analyses of the GRAV residue of the total extract samples are summarized in Table 3-9. As noted, only the spectra of the XAD-2 and bottom ash extracts were sufficiently strong to be interpreted. The spectra for both extracts were consistent with the presence of aliphatic hydrocarbons and oxygenated species, such as carboxylic acids, aldehydes, and alcohols.

3.4.3 LC Fractionation of Extracts

The XAD-2 and bottom ash sample extracts contained greater than 15 mg of total organic, so they were separated into seven polarity fractions via

TABLE 3-8. SUMMARY OF ASH STREAM TOTAL ORGANIC CONTENT

	Test 2 (mg/kg)
Semivolatile organics analyzed by TCO	
Bottom ash	1,600
Baghouse hopper ash	7.2
Nonvolatile organics analyzed by gravimetry	
Bottom ash	6,400
Baghouse hopper ash	<100

TABLE 3-9. SUMMARY OF INFRARED SPECTRA OF TOTAL SAMPLE EXTRACTS

Extract sample	Wave number (cm^{-1})	Assignment	Possible compound categories present
10μ + 3μ particulate	No peaks		
Filter + 1μ particulate	No peaks		
XAD-2 + OMC	3600 to 3000	O-H stretch	Oxygenated hydrocarbons such as carboxylic acids, aldehydes, alcohols; possible aromatics.
	1640	C=C[a] stretch	
	1410	O-H bend	
	1160 to 1060	C-O stretch	
	1000	Not assigned	
Bottom ash	3400	O-H stretch	Aliphatic hydrocarbons; oxygenated hydrocarbons such as carboxylic acids, ketones, aldehydes, alcohols; possible aromatics.
	2940	C-H alkyl	
	2860	C-H alkyl	
	1730	C=O stretch	
	1610	C•••C aromatic[a]	
	1460	C-H bend	
	1380	C-C stretch	
	1280	C-O stretch	
	820	Not assigned	
	750	C-H rock	
Baghouse ash	No peaks		

[a]Tentative assignment, not supported by other absorbances

liquid column chromatography. The gravimetric and TCO content of each fraction are summarized in Tables 3-10 (XAD-2) and 3-11 (bottom ash). Table 3-10 shows that very poor recovery was achieved in the LC fractionation of the XAD-2 extract (about 16 percent), with recovery of the TCO fraction being especially poor. Most of the material appeared to be retained on the chromatography column. The analyst noted that the XAD-2 extract appeared to consist of two distinct liquid phases. It is possible that one of these phases could not be eluted from the column with the specified series of solvents. Most of the XAD-2 extract which did elute from the column occurred in LC fraction 7. This fraction generally contains carboxylic acids and other polar (e.g. oxygenated) compounds.

The bottom ash extract exhibited a more even distribution of organic content among the LC fractions. LC 1 accounted for most of the total organic and virtually all of the semivolatile (TCO) content. Other fractions showed considerable, though lesser, amounts of nonvolatile (GRAV) organics. Fractionation recovery, at 119 percent, was considerably better for this sample.

3.4.4 IR Spectra of LC Fractions

The results of the IR analysis of the GRAV residue of the eluted LC fractions are summarized in Table 3-12 (XAD-2 extract) and in Table 3-13 (bottom ash extract). For the XAD-2 extract, only the LC 7 residue had an IR spectrum sufficiently strong to interpret. This spectrum is consistent with the presence of polar oxygenated species such as carboxylic acids, which elute in LC 7. Comparing Table 3-12 with Table 3-9 confirms that the LC 7 IR spectrum is essentialy the same as that obtained for the total sample extract.

TABLE 3-10. LC FRACTIONATION OF THE XAD-2 EXTRACT

	TCO (mg)	GRAV (mg)	TCO + GRAV (mg)	Concentration (mg/dscm)
Total sample	53	285	338	37.8
Taken for LC	15	83	98	11.0
Recovered	0.16	15.4	16	1.8

	TCO (mg)		GRAV (mg)			
Fraction	Analyzed[a]	Corrected to total sample	Analyzed[a]	Corrected to total sample	TCO + GRAV (mg)	Concentration (mg/dscm)
1	<0.02	<0.07	0.8	2.8	2.8	0.31
2	<0.01	<0.03	0.4	1.4	1.4	0.16
3	<0.01	<0.03	0.6	2.1	2.1	0.23
4	0.13	0.45	0.6	2.1	2.6	0.29
5	0.03	0.10	0.4	1.4	1.5	0.17
6	<0.01	<0.03	0.6	2.1	2.1	0.23
7	<0.01	<0.03	12.0	41.2	41.2	4.62
Total	0.16	0.55	15.4	53.1	53.7	6.01

[a]Blank corrected

TABLE 3-11. LC FRACTIONATION OF THE BOTTOM ASH EXTRACT

	TCO (mg)	GRAV (mg)	TCO + GRAV (mg)	Concentration (mg/kg)
Total sample	40	160	200	8,000
Taken for LC	20	80	100	4,000
Recovered	3.6	115.8	119.4	4,780

	TCO (mg)		GRAV (mg)			
Fraction	Analyzed[a]	Corrected to total sample	Analyzed[a]	Corrected to total sample	TCO + GRAV (mg)	Concentration (mg/kg)
1	3.3	6.6	34.0	68.0	74.6	2,980
2	0.10	0.20	23.0	46.0	46.2	1,850
3	0.06	0.12	15.6	31.2	31.3	1,250
4	0.09	0.18	10.4	20.8	21.0	850
5	0.09	0.18	11.0	22.0	22.2	890
6	<0.01	<0.02	16.2	32.4	32.4	1,300
7	<0.01	<0.02	5.6	11.2	11.2	450
Total	3.6	7.3	115.8	231.6	238.9	9,560

[a]Blank corrected

TABLE 3-12. IR SPECTRUM SUMMARY: XAD-2 EXTRACT, LC 7[a]

Wave number (cm-1)	Intensity[b]	Assignment	Possible compound categories present
3400	S	O-H stretch	Oxygenated hydrocarbons such as carboxylic acids
1640	S	C=C stretch	
1550	W	Not assigned	
1390	M	O-H bend	
1220	W	C-O stretch	
1100	W	C-O stretch	

[a]Only LC 7 had a spectrum sufficiently strong to interpret
[b]S = strong, M = moderate, W = weak

TABLE 3-13. IR SPECTRA SUMMARY: BOTTOM ASH EXTRACT LC FRACTIONS

Wave number (cm^{-1})	Assignment	Intensity[a]						
		LC 1	LC 2	LC 3	LC 4	LC 5	LC 6	LC 7
3500	O-H stretch			W				
3450 to 3400	O-H stretch			W	W	M	M	
3300	O-H stretch							W
3060	C-H stretch			M				
2950 to 2940	C-H stretch	S	S	S	S	S	S	S
2870 to 2860	C-H stretch	M						
1740 to 1720	C=O stretch				M	S	M	
1620 to 1610	C=C stretch	W		M	W	M	M	M
1480 to 1460	C-H bend	M	M	S	M	M	M	M
1390 to 1380	C-H bend, O-H bend	W		M	W	W	M	W
1290 to 1270	C-O stretch			W	M	M	M	W
1200	C-O stretch			W				
1140	C-O stretch				W	M		
1080	C-O stretch				W	M		
1040 to 1020	C-O stretch			W	W	W		
960	C-C stretch			W	W			
880	C-H rock	W	W	M				
820	C-H rock	W	W	M	W	W	W	
760 to 750	C-H rock	W	M	M	W	W	W	W
710	Not assigned			W	W	W	W	

[a] S = strong, M = moderate, W = weak, blank = absorbance not in spectrum

The IR spectra of the bottom ash fractions are summarized in Table 3-11. The spectra of LC 1 and 2 are consistent with the presence of aliphatic hydrocarbons, which elute in those fractions. The spectra of LC 3 and 4 are consistent with the possible presence of aldehydes and ethers which elute in those fractions. The spectra of LC 5, 6, and 7 suggest the presence of more polar oxygenates, such as ketones, esters, phenols, and carboxylic acids which elute in those fractions.

Comparing the Table 3-13 summary with Table 3-9 shows that all absorbences found in the total extract sample are accounted for among the eluted LC fractions. In fact, a few fractions had weak to moderate absorbences that could not be elucidated in the total extract spectrum.

3.4.5 Low Resolution Mass Spectrometry Analysis of LC Fractions

Direct injection probe LRMS was performed on various combinations of LC fractions of the XAD-2 and bottom ash extract samples and the total baghouse hopper ash extract. The results of these analyses are presented in Table 3-14. Specific compound categories were identified as being present only in two LC fractions of the bottom ash extract and the baghouse ash extract. Alkyl aromatics were identified in all three samples. The results from the bottom ash extract are in reasonable agreement with the IR spectra results in that they indicate carboxylic acids and alkyl aromatics in the LC fraction where they are expected to be found.

The inability to identify any compound categories in the LRMS analyses of the XAD-2 extract LC fraction is no doubt due to the very poor recovery of the LC fractionation performed, although one might have expected some identifications in the total extract and perhaps the LC 7 extract, as these contained moderate organic content. Similarly, some identifications might

TABLE 3-14. LRMS ANALYSIS RESULTS

Sample	Compound category	MW range	Intensity
Composite particulate extract	None identified		
XAD-2 + condensate:			
Total extract	None identified		
LC 1 + 2 + 3	None identified		
LC 4 + 5 + 6	None identified		
LC 7	None identified		
Bottom ash extract:			
LC 1	None identified		
LC 2	None identified		
LC 3	None identified		
LC 4	None identified		
LC 5	Alkyl aromatics	106 to 148	100
LC 6	Alkyl aromatics Carboxylic acids	106 to 148 --	100 100
LC 7	None identified		
Baghouse ash extract	Alkyl aromatics Halogenated aliphatics	106 to 148 --	100 100

have been expected for the LC 1 through 4 fractions of the bottom ash extracts. The authors have no explanation for these inabilities to identify major component categories.

3.4.6 Gas Chromatography/Mass Spectrometry Analysis of Total Sample Extracts

GC/MS analyses of the SASS train sample extracts (10 plus 3 μm particulate, 1 μm plus filter particulate, XAD-2 and organic module condensate) and extracts of the bottom ash and baghouse ash were performed to detect and quantify the 58 semivolatile organic priority pollutant species, a class which contains several polynuclear aromatic hydrocarbon (PAH) compounds of interest in combustion source emissions. The compounds sought in the analysis and their detection limits are listed in Table 3-15. Table 3-16 lists the compounds detected in terms of a mass concentration (mg/kg) and a flue gas concentration (μg/dscm), as appropriate. The greatest quantity of PAH and other organic priority pollutant compounds occurred in the bottom ash. This is consistent with the high TCO and GRAV analysis results noted in Section 3.4.1. In fact, of the PAH compounds, only naphthalene was found in samples other than the bottoh ash. The phthalates noted in the table are suspected contaminants.

In addition to specific quantification of semivolatile organic priority pollutants in the GC/MS analyses, major peaks representing other organic species in the GC chromatograms present at significant concentrations were identified and approximately quantitated. Table 3-17 shows the organic compounds identified in each sample and their concentrations. Most of those noted are aromatic organics, fused ring aromatics, or alkyl derivatives of these. As in other analyses, the greatest number and greatest quantities of

TABLE 3-15. COMPOUNDS SOUGHT IN THE GC/MS ANALYSIS AND THEIR DETECTION LIMITS (ng/µl injected)

Acid Compounds			
2,4,6-trichlorophenol	5	2-nitrophenol	5
p-chloro-m-cresol	5	4-nitrophenol	20
2-chlorophenol	5	2,4-dinitrophenol	20
2,4-dichlorophenol	5	4,6-dinitro-o-cresol	20
2,4-dimethylphenol	5	pentachlorophenol	5
		phenol	1
Base Neutral Compounds			
1,2,4-trichlorobenzene	1	benzo(c)phenathrene	40
1,2-dichlorobenzene	1	bis(2-chloroethoxy)methane	1
1,2-diphenylhydrazine (as azobenzene)	1	bis(2-chloroethyl)ether	1
		bis(2-chloroisopropyl)ether	1
1,3-dichlorobenzene	1	bis(2-ethylhexyl)phthalate	1
1,4-dichlorobenzene	1	butyl benzyl phthalate	1
2,4-dinitrotoluene	1	chrysene	1
2,6-dinitrotoluene	1	di-n-butyl phthalate	1
2-chloronaphthalene	1	di-n-octyl phthalate	1
3,3'-dichlorobenzidine	5	dibenzo(a,h)anthracene	5
3-methyl cholanthrene	40	dibenzo(c,g)carbazole	40
4-bromophenyl phenyl ether	1	diethyl phthalate	1
4-chlorophenyl phenyl ether	1	dimethyl phthalate	1
7,12-dimethyl benz(a)anthracene	40	fluoranthene	1
N-nitrosodi-n-propylamine	5	fluorene	1
N-nitrosodimethylamine	NA	hexachlorobenzene	1
N-nitrosodiphenylamine	1	hexachlorobutadiene	1
acenaphthene	1	hexachlorocyclopentadiene	1
acenaphythylene	1	hexachloroethane	1
anthracene	1	indeno(1,2,3-cd)pyrene	5
benzo(ghi)perylene	5	isophorone	1
benzidine	20	naphthalene	1
benzo(b)fluoranthene	1	nitrobenzene	1
benzo(k)fluoranthene	1	perylene	40
benzo(a)anthracene	1	phenanthrene	1
benzo(a)pyrene	1	pyrene	1

TABLE 3-16. PAH AND OTHER SEMIVOLATILE ORGANIC PRIORITY POLLUTANT SPECIES DETECTED

Species	Sample						
	10 + 3 μm particulate		1 μm + filter particulate		XAD + condensate extract	Bottom ash	Baghouse ash
	(mg/kg)	(μg/dscm)	(mg/kg)	(μg/dscm)	(μg/dscm)	(mg/kg)	(mg/kg)
PAH's							
Acenaphthene	--[a]	--	--	--	--	1	--
Acenaphthylene	--	--	--	--	--	2	--
Anthracene	--	--	--	--	--	1	--
Benz(a)anthracene	--	--	--	--	--	0.4	--
Benzo(j+k)fluoranthenes	--	--	--	--	--	0.4	--
Chrysene	--	--	--	--	--	0.8	--
Fluoranthene	--	--	--	--	--	2	--
Fluorene	--	--	--	--	--	2	--
Naphthalene	0.2	0.9	3.7	7.7	--	42	0.3
Phenanthrene	--	--	--	--	--	11	--
Pyrene	--	--	--	--	--	2	--
Other priority pollutants							
Bis(2-ethylhexyl)phthalate	<0.15	<0.7	3.4	7.2	7.8	84	0.3
Butylbenzylphthalate	<0.07	<0.3	0.2	0.4	2	120	0.08
Diethylphthalate	--	--	0.4	0.8	--	--	0.04
2,4-dimethylphenol	<0.2	<0.9	<0.4	<0.8	<7	5	<0.2
Detection limit	0.05	0.2	0.05	0.1	1.1	0.4	0.04

[a]Double dashes denote less than detection limit noted

TABLE 3-17. OTHER COMPOUNDS TENTATIVELY IDENTIFIED IN GC/MS ANALYSES

Sample	Compound	Concentration (mg/kg)	Concentration (µg/dscm)
10 + 3 µm particulate	No peaks identified		
1 µm + filter particulate	C_3-alkylbenzene	4.7	9.8
	Trimethylbenzene	2.0	4.1
	C_4-aklylbenzene	0.8	1.7
	Benzothiazole	3.9	8.2
XAD + condensate extract	Benzoic acid	--	290
	Ethylbenzoic acid	--	58
	Ethylbenzaldehyde	--	17
Bottom ash	Sulfur	100	--
	Methylnaphthalene	110	--
	Ethylnaphthalene	14	--
	Dimethylnaphthalene	29	--
	Trimethylnaphthalene	47	--
	Dibenzofuran	13	--
	4-methyldibenzofuran	17	--
Baghouse ash	No peaks identified	--	--

these species were found in the bottom ash. The presence of these compounds, as indicated by GC/MS confirms the results of the LRMS analysis which indicated the presence of alkyl aromatics in the bottom ash extract.

REFERENCES FOR SECTION 3

3-1. DeRosier, R., "Environmental Assessment of a Watertube Boiler Firing a Coal/Oil Mixture," Acurex Report TR-81-87/EE, March 1984.

3-2. DeRosier, R., "Environmental Assessment of a Crude-Oil Heater Using Staged Air Lances for NO_x Reduction," Acurex Report TR-82-94/EE, March 1984.

3-3. Castaldini, C., et al., "Environmental Assessment of NH_3 Injection for an Industrial Package Boiler," Acurex Draft Report TR-82-94/EE, March 1984.

3-4. DeRosier, R., et al., "Environmental Assessment of a Commercial Boiler Firing a Coal/Plastic Waste Mixture," Acurex Draft Report under EPA Contract 68-02-3188, February 1985.

3-5. VanBuren, D., and L. R. Waterland, "Environmental Assessment of a Coal-Water-Slurry-Fired Industrial Boiler," Acurex Draft Report TR-84-155/EE, March 1985.

3-6. Castaldini, C., et al., "Environmental Assessment of an Enhanced Oil Recovery Steam Generator Equipped with a Low-NO_x Burner," Acurex Draft Report TR-84-161/EE, September 1984.

3-7. Castaldini, C., et al., "Environmental Assessment of an Enhanced Oil Recovery Steam Generator Equipped with the EPA Low NO_x Burner," Acurex Draft Report TR-85-174/33D, January 1985.

3-8. Lentzen, D. E., et. al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)", EPA 600/7-78-201, NTIS PB293795, October 1978.

3-9. Waterland, L. R. et al., "Environmental Assessment of Stationary Source NO_x Control Technologies -- Final Report," EPA 600/7-82-034, NTIS PB82-249350, May 1982.

SECTION 4

ENVIRONMENTAL ASSESSMENT

This section discusses the potential environmental significance of firing a coal-water slurry in the boiler tested and also discusses the results of the bioassay testing of samples collected during the tests. As a means of ranking species discharged for possible further consideration, flue gas stream species concentrations are compared to occupational exposure guidelines. Bioassay analyses were conducted as a more direct measure of the potential health effects of the emissions and effluent streams. Both of these analyses are aimed at identifying potential problem areas and providing the basis for ranking pollutant species and discharge streams for further consideration.

4.1 EMISSION ASSESSMENT

To obtain a measure of the potential significance of the discharge streams analyzed in this test program, discharge stream concentrations were compared to an available set of health-effects-related indices. For the flue gas discharge, the indices used for comparison were occupational exposure guidelines. Two sources of such guidelines were used: the time-weighted-average TLV's defined by the American Conference of Governmental Industrial Hygienists (AGCIH) (Reference 4-1) and 8-hr time-weighted-average exposure limits established by the Occupational Safety and Health Adminstration (OSHA) (Reference 4-2).

The comparisons of discharge stream species concentrations to these indices should only be used for ranking species emission levels for further testing and analyses.

Table 4-1 lists those polluant species emitted in the flue gas at levels greater than 10 percent of their occupational exposure guideline. As noted in the table, many trace elements were present at the boiler outlet at significant levels. However, flue gas particulate accounts for the major fraction of these elements in the flue gas at this location. Ultimate flue gas discharge concentrations would be significantly reduced after passage through a particulate control device.

For comparison, the gaseous criteria pollutants SO_2 and NO_x were emitted at levels much higher than their occupational exposure guidelines. NO_x emissions were at levels about 100 times its occupational exposure guideline. SO_2 emissions were at levels about 500 times its occupational exposure guidelines.

4.2 BIOASSAY RESULTS

Health effects bioassay tests were performed on the SASS organic sorbent (XAD-2) extracts and particulate sample, the bottom ash and the baghouse hopper ash. The bioassay tests performed were (Reference 4-3) (1) the Ames assay, based on the property of Salmonella typhinurium mutants to revert due to exposure to various classes of mutagens, and (2) the cytotoxicity assay (CHO) with mammalian cells in culture to measure cellular metabolic impairment and death resulting from exposure to soluble toxicants.

Table 4-2 summarizes the results of these tests. The results suggest that the XAD-2 extract was of low mutagenicity and undetermined (low or less)

TABLE 4-1. FLUE GAS POLLUTANTS EMITTED AT CONCENTRATIONS EXCEEDING 10 PERCENT OF THEIR OCCUPATIONAL EXPOSURE GUIDELINE

Species	Flue gas concentration (mg/dscm)	Occupational exposure guideline[a] (mg/m^3)
SO_2	2,480	5
Iron, Fe	201	1
Phosphorus, P	13.2	0.1
Aluminum, Al	297	2
NO_x (as NO_2)	626	6
Arsenic, As	1.06	0.01[c]
Silicon, Si	537	10[b]
Vanadium, V	1.67	0.05
Chromium, Cr	1.19	0.05
Beryllium, Be	0.045	0.002
Copper, Cu	2.03	0.1[c]
Lead, Pb	0.85	0.05[c]
Barium, Ba	7.95	0.5
Nickel, Ni	1.33	0.1
Calcium, Ca	25.3	2
Lithium, Li	0.27	0.025
Potassium, K	19.3	2[d]
Cobalt, Co	0.64	0.1
CO	240	55
Titanium, Ti	20	10[b]
Uranium, U	0.09	0.05[c]
Magnesium, Mg	15	10
Silver, Ag	0.0095	0.010
Selenium, Se	0.167	0.2
Cadmium, Cd	0.0338	0.05[d]
Sodium, Na	1.09	2[d]
Manganese, Mn	>1.7	5[d]
Germanium, Ge	0.13	0.6
Zirconium, Zr	1.16	5
Antimony, Sb	0.0899	0.5
Zinc, Zn	0.632	1
Thallium, Tl	0.0126	0.1

[a]Time-weighted-average TLV (Reference 4-1) unless noted
[b]For nuisance particulate
[c]8-hr time-weighted-average OSHA exposure limit (Reference 4-2)
[d]Ceiling limit

TABLE 4-2. BIOASSAY RESULTS

Sample	Ames mutagenicity	CHO clonal toxicity
10 + 3 μm particulate	ND	L/M
1 μm + filter particulate	ND	ND/L
XAD-2 + organic module condensate total extract	L	U(L)
Bottom ash	ND	L/M
Baghouse ash	ND	L

Note
ND -- No detectability mutagenicity/toxicity
L -- Low mutagenicity/toxicity
M -- Moderate mutagenicity/toxicity
U -- Undetermined toxicity. Exact toxicity range could not be determined due to insufficient amount of sample. Test results indicate low toxicity or less.

toxicity. The other samples showed no detectable mutagenicity and low to moderate toxicity. The positive Ames response for the XAD-2 extract is typical for XAD-2 from SASS tests of combustion sources. Current studies sponsored by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, are investigating whether such a response is due to artifact compounds formed when combustion product gas containing NO_x is passed over XAD-2 resin.

4.3 SUMMARY

A comprehensive emissions testing program was performed on a watertube industrial boiler fired with a coal-water slurry (CWS). The slurry fired contained nominally 60 percent coal by weight. Two tests were performed: an abbreviated set of tests with the unit fired at about 2.8 percent flue gas O_2

(test 1), and a comprehensive set of tests with the unit fired at about 2.1 percent O_2 (test 2).

NO_x, SO_2, CO, and TUHC emissions (corrected to 3 percent O_2) averaged about 230 and 310 ppm, 880 and 960 ppm, 170 and 200 ppm, and 1 and 3 ppm, respectively for test 1 and 2, respectively. The apparent emission differences for these pollutants between the two tests are not considered significant. N_2O levels in the flue gas were generally 15 to 25 percent of the corresponding NO_x emission level.

Particulate levels at the boiler outlet (upstream of the unit's particulate control device) were quite high. These also apparently increased from about 3.5 g/dscm in test 1 to 7.3 g/dscm in test 2. The increase is attributed to greatly increased combustible losses in the flyash in test 2. Confirming this is the fact that the emitted particle size distribution was dominated by coarse particulate; over 60 percent (weight) of the boiler outlet particulate was larger than 10 μm, almost 70 percent was larger than 3 μm.

Total organic emissions in test 2 (the comprehensive emissions test) were quite high, almost 50 mg/dscm. About 70 percent of this organic matter was in the nonvolatile (greater than 300°C, C_{16+}) boiling point range.

The bottom ash organic content was quite high as well, 8 g/kg, with 80 percent of this being in the nonvolatile boiling point range. Alkyl aromatics and carboxylic acids were the major compound categories identified in the bottom ash organic fraction.

Of the polynuclear aromatic hydrocarbon (PAH) compounds analyzed, only naphthalene was found in flue gas samples (on the particulate), with emission

levels of 8.6 µg/dscm. Several PAH's were found in the bottom ash at levels ranging from 0.4 to over 40 mg/kg.

REFERENCES FOR SECTION 4

4-1. "Threshold Limit Values for Chemical Substances and Physical Agents in the Work Environment with Intended Changes for 1983-84," American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1983.

4-2. OSHA Safety and Health Standards, 29 CFR 1910, Subpart Z.

4-3. Brusick, D. J., and R. R. Young, "IERL-RTP Procedures Manual: Level 1 Environmental Assessment, Biological Tests," EPA-600/8-81-024, NTIS PB81-228766, October 1981.

SECTION 5

TEST QUALITY ASSURANCE AND QUALITY CONTROL

Quality assurance (QA) activities, implemented for this test included:

- Duplicate injections for C_1 to C_6 hydrocarbons
- Duplicate injections for N_2O
- Duplicate total chromatographable organics (TCO) analysis
- Duplicate gas chromatography/mass spectrometry (GC/MS) analysis for the semivolatile organic priority pollutant
- Blind standard analysis for Hg analysis

The following paragraphs discuss the results of these QA activities.

5.1 C_1 to C_6 HYDROCARBON PRECISION

Replicate injections were performed for the C_1 to C_6 calibration standards and at least one duplicate injection of sample per test. The area counts and relative standard deviations (RSD) from these injections are presented in Table 5-1. The replicate standard injections were performed with a gas mixture including the six normal C_1 to C_6 hydrocarbons. In all cases, the percent RSD is below the QA objective of 15 percent precison for the standard injections (Reference 5-1). The duplicate sample injection for test 2 had an RSD of 26 percent, which failed the QA objective. Both duplicate injections from test 1 met the QA objective. Thus, of a total of 15 determinations, all but one met the QA precision goal, for a percent completeness of 93 percent, exceeding the QA objective of 90 percent.

TABLE 5-1. AREA COUNTS AND RELATIVE STANDARD DEVIATIONS FOR C_1 TO C_6 ANALYSES

	Test 1 Injection number area count					RSD (percent)
	1	2	3	4	5	
Calibration standards						
C1	7,192	6,605	7,076	7,195	6,966	3.5
C2	9,299	9,263	9,184	9,215	9,235	0.5
C3	10,211	10,239	10,107	10,477	10,258	1.3
C4	17,917	17,874	17,819	18,212	17,996	0.9
C5	23,420	23,095	23,103	23,603	24,080	1.7
C6	29,567	30,115	30,902	29,835	29,104	2.2
Samples (total count)	1,560	1,554				0.3
	4,808	4,316				7.6

	Test 2 Injection number area count							RSD (percent)
	1	2	3	4	5	6	7	
Calibration standards								
C1	7,860	7,497	7,644	7,290	8,507	8,131	9,017	7.6
C2	9,503	9,516	9,732	9,486	10,149	10,427	10,511	4.5
C3	10,417	10,769	10,872	10,380	10,681	12,675	11,078	7.2
C4	18,491	18,606	18,969	18,561	18,821	19,184	19,160	1.5
C5	23,987	24,000	24,391	25,759	24,385	24,947	24,630	2.5
C6	30,131	29,793	30,948	30,900	30,513	30,986	30,120	1.6
Samples (total count)	1,616	2,337						25.8

5.2 N_2O PRECISION

Replicate injections were performed for N_2O standards and samples. Table 5-2 summarizes the area counts for N_2O and the percent RSD for these runs. All of the standard injections met the QA objective of 20 percent RSD (Reference 5-1). The replicate injections of the samples also met the QA objectives.

5.3 TCO PRECISION

Duplicate injections of the XAD-2 plus organic module condensate extract were performed in the quantitation of total semivolatile organics. Results of the duplicate injections were 57 and 49 mg TCO per SASS train. This corresponds to an RSD of 10.7 percent, just failing QA objective of 10 percent RSD for this analysis.

5.4 GC/MS PRECISION

Duplicate injections of the XAD-2 plus organic module condensate extract were performed in the GC/MS analysis for the semivolatile organic priority pollutants. Quantitation results (only the two compounds identified and quantitated) are summarized in Table 5-3. The average RSD is within the QA objective (Reference 5-1) of 50 percent for this analysis. The objective was failed for one compound quantitation; however, this compound was only found at the detection limit of the analysis.

5.5 MERCURY ANALYSIS

A NBS reference flyash with a 0.13 mg/kg mercury concentration was submitted to the analytical laboratory as a blind sample for analysis. The reported concentration was 0.09 mg/kg, corresponding an accuracy of -30 percent. This is outside the QA objective of ±20 percent.

TABLE 5-2. AREA COUNT AND RELATIVE STANDARD DEVIATIONS FOR N_2O ANALYSES

Sample	Injection number area count 1	2	3	4	RSD (percent)
Calibration standards	79,597	79,456	--	--	0.1
	10,258	10,154	--	--	0.7
	71,978	60,990	67,879	57,102	10.9
Test 1					
Sample 1	24,016	23,984	--	--	0.1
Sample 2	28,974	28,501	--	--	1.2
Sample 3	21,196	27,177	23,624	--	12.5
Test 2					
Sample 1	55,252	78,040	81,048	--	19.7
Sample 2	73,009	72,283	--	--	0.7
Sample 3	88,851	91,203	--	--	1.8
Sample 4	36,812	37,539	--	--	1.4

TABLE 5-3. DUPLICATE ANALYSIS RESULTS AND RELATIVE STANDARD DEVIATIONS FOR THE GC/MS ANALYSES

Compound quantitated	Analysis result (µg/ml) Run 1	Run 2	RSD (percent)
bis (2-ethylhexyl) phthalate	6	6	0
butylbenzyl phthalate	3	1	70.7
Average			35.4

5.6 QA SUMMARY

In summary, of all QA activities performed to challenge the precision of analytical techniques employed, results were within the project QA objectives in all instances except two. One failure was in the duplicate TCO analysis, where measured precision was 10.7 percent compared to a project objective of 10 percent. This very small failure to obtain the QA objective is not considered significant, and has no effect on conclusions derived from data obtained in the tests.

The second failure was in the GC/MS analysis, where for one compound method precision was 71 percent compared to the project objective of 50 percent. However, the quantitations for this compound were at the detection limit of the analytical techniques, an area where precision is always poor. This QA objective failure is also not considered significant, and has no effect on conclusions derived from data obtained in the tests.

In the one test performed to challenge the accuracy of the cold vapor AAS technique employed to measure mercury concentration, analysis of a blind audit sample gave a result with accuracy of -30 percent, compared to a project objective of ±20 percent. This failure has no effect on test program conclusions since mercury was not detected in any test sample analyzed.

REFERENCE FOR SECTION 5

5-1. "Quality Assurance Plan for the Combustion Modification Environmental Assessment," prepared under EPA Contract No. 68-02-3188, September 10, 1982.

APPENDIX A

TEST EQUIPMENT AND PROCEDURES

A.1 CONTINUOUS MONITORING SYSTEM

Flue gas compositon of O_2, CO_2, CO, SO_2, NO_x, NO, and unburned hydrocarbons were measured continuously by instrumentation at the test facility. Flue gas samples were drawn by a pump suction through a Pall particulate filter into a compressed air dryer. The samples were further dried by a Perma Pure Dryer before delivery to the gas analyzers. Table A-1 lists the instrumentation available at the test facility for this test program.

A.2 PARTICULATE AND SULFUR OXIDE EMISSIONS

Particulate mass emissions and sulfur oxides tests were conducted in accordance with EPA Reference Methods 5 and 8. The Acurex High Volume Stack Samples (HVSS), illustrated schematically in Figure A-1, was used in this program. A 1.52m (5-ft) heated stainless steel glass-lined probe was maintained at 120°C (250°F) as required by EPA Method 5. A glass fiber 142-mm (5.59-in.) diameter filter was used to capture the particulate in the heated oven. The impinger train consisted of four glass impingers equipped with Teflon caps and 316 stainless steel stems, collector tubes, and fittings. The first impinger contained 100 ml of 80 percent isopropanol in distilled water, the second and third impinger contained 100 ml of 3 percent H_2O_2 and the fourth contained a known amount of silica gel. A fritted glass

TABLE A-1. CONTINUOUS MONITORING EQUIPMENT

Flue gas component	Analyzer	Principle of operation	Mode	Range[a]
O_2	Beckman Oxygen Analyzer	Magnetic susceptibility	Model 755	0 to 25 percent
SO_2	MSA LIRA Infrared Analyzer	Infrared absorption	Model 303	0 to 2,000 ppm
CO_2				0 to 25 percent
CO				0 to 1,000 ppm
NO/NO_x	Beckman NO/NO_x Analyzer	Chemiluminescent	Model 951	0 to 1,000 ppm
THC	Beckman Hydrocarbon Analyzer	Flame ionization	Model 400	0 to 100 ppm

[a]Operating ranges during the COM test burn on February 19, 1981

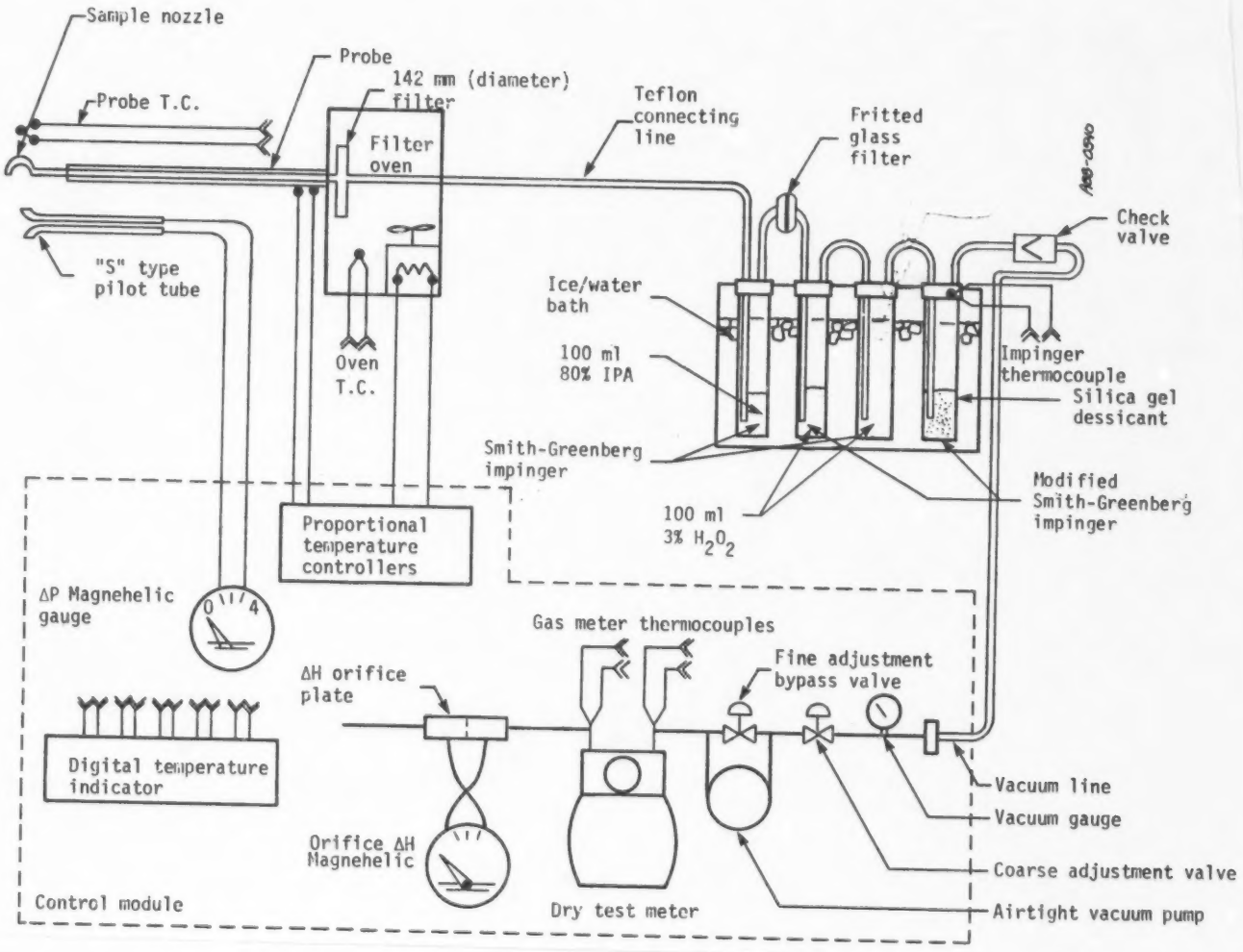


Figure A-1. Schematic of particulate and SO_x sampling train (EPA Method 5 and 8).

filter is placed between the first and second impingers. The control module was equipped with magnahelic gauges and digital thermocouple readouts, and a dry gas flowmeter for monitoring pressure and temperature in the stack and total gas sampled.

Sample collection took place in the uninsulated stack above the ID fan. The particulate tests were performed at 12 sampling points in accordance with EPA Method 1. Each test point was sampled for 6 min, hence a 72-min total sampling time.

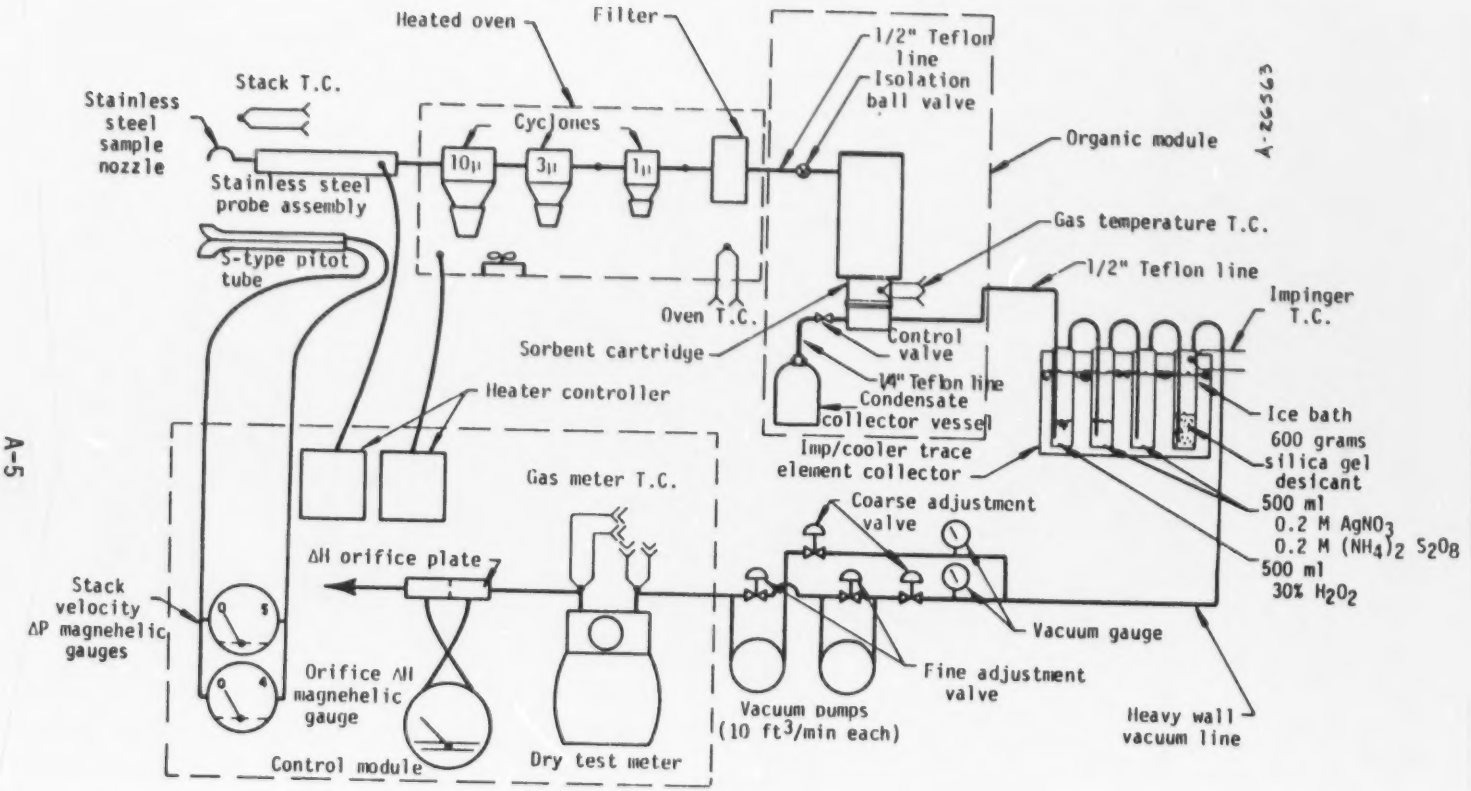
SO_2 and SO_3 emissions were measured by titration of the impinger solutions per EPA Method 8. Sulfuric acid mist and any vapor phase SO_3 is trapped in the isopropanol impinger with the backup filter trapping any carryover mist. SO_2 is absorbed in the H_2O_2 impingers. After completion of a test, the filter is rinsed with isopropanol and the rinse solution added to the isopropanol impinger solution. Absorbed SO_3 in the isopropanol and SO_2 in the H_2O_2 are determined separately by barium-thorin titration.

A.3 TRACE ELEMENT AND ORGANIC EMISSIONS

Emissions of inorganic trace elements and organic compounds were sampled with the source assessment sampling system (SASS). Designed for Level 1 environmental assessment (Reference A-1), the SASS collects large quantities of gas and solid samples required for subsequent analyses of inorganic and organic emissions as well as particle size measurement.

The SASS, illustrated in Figure A-2, is generally similar to the system utilized for total particulate mass emission tests (HVSS) with the exception of:

- Particulate cyclones heated in the oven with the filter to 230°C (450°F)



A-5

Figure A-2. SASS train schematic.

- The addition of a gas cooler and organic sampling module
- The addition of necessary vacuum pumps

Schematics outlining the sampling and analytical procedures using the SASS equipment are presented in Figures A-3 and A-4. The following briefly describes analytical procedures used in measuring boiler outlet trace elements and organic emissions.

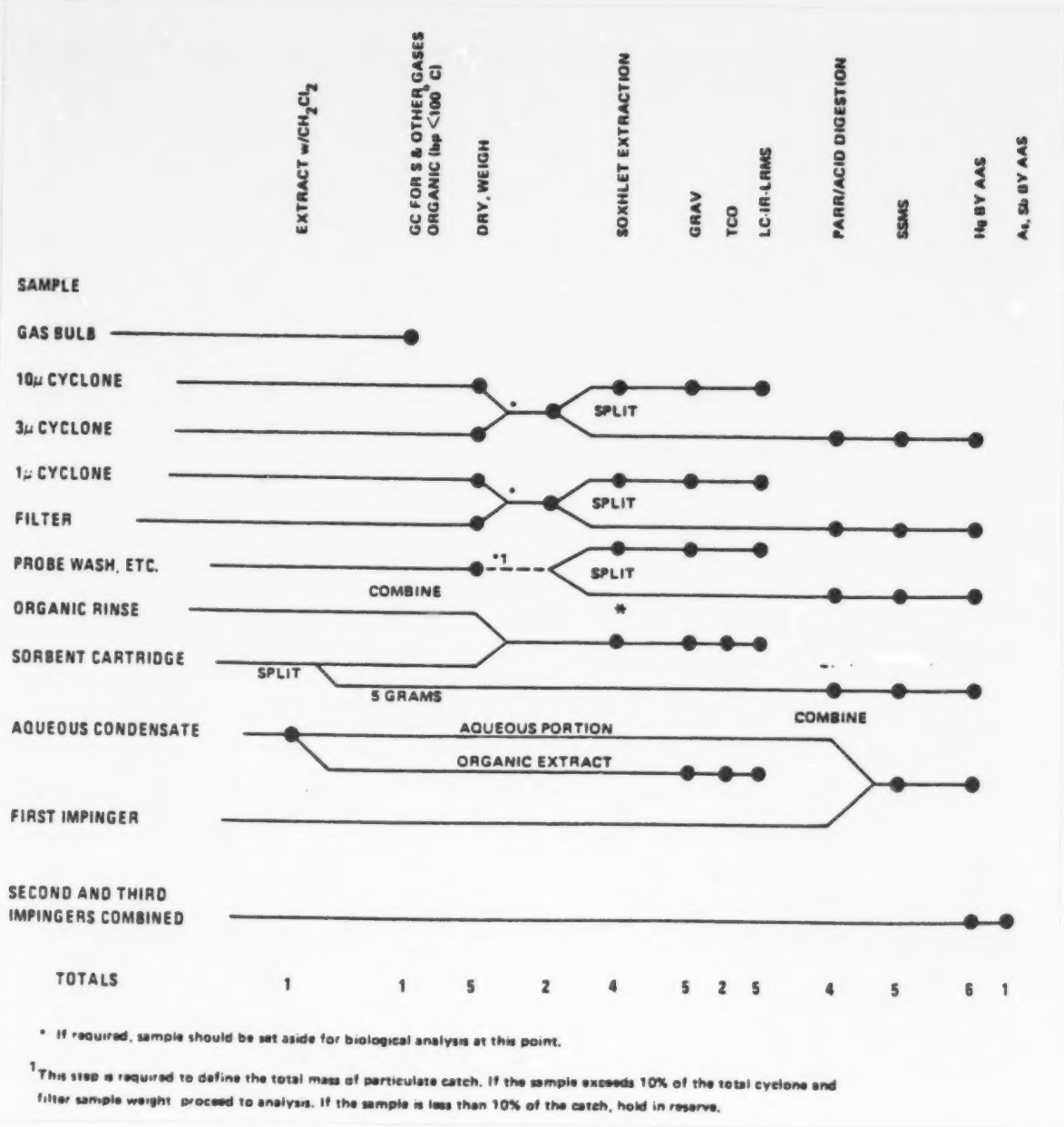
Inorganic analyses of solid and liquid samples from the SASS train were performed with spark source mass spectroscopy (SSMS) for most of the trace elements. Atomic absorption spectrometry (AAS) was used for analyses of volatile mercury (Hg), antimony (Sb), and arsenic (As) and for backup analyses for those elements identified as major components by SSMS.

Quantitative information on total organic emissions was obtained by gas chromatography for total chromatographable organics (TCO) and by gravimetry (GRAV) of particulate, sorbent module (XAD-2), and condensate trap organic extracts. Infrared spectroscopy (IR) was used for identification of organic functional groups and gas chromatography/mass spectroscopy (GC/MS) was used to quantitate the semivolatile organic priority pollutant species in extract samples. This class contains several of the polynuclear aromatic hydrocarbon (PAH) compounds of interest from combustion sources. Figure A-6 illustrates the organic analysis methodology followed during the current program.

A.4 C_1 TO C_6 HYDROCARBON SAMPLING AND ANALYSIS

Samples of flue gas were collected for C_1 to C_6 hydrocarbon analysis using a grab sampling procedure.

The samples were collected using the apparatus illustrated in Figure A-6. The equipment consisted of a heated, 0.64-cm (1/4-in.) OD pyrex-lined, stainless-steel probe fitted with a 0.7-μm sintered stainless



* If required, sample should be set aside for biological analysis at this point.

[1] This step is required to define the total mass of particulate catch. If the sample exceeds 10% of the total cyclone and filter sample weight proceed to analysis. If the sample is less than 10% of the catch, hold in reserve.

Figure A-3. Flue gas analysis protocol for SASS samples.

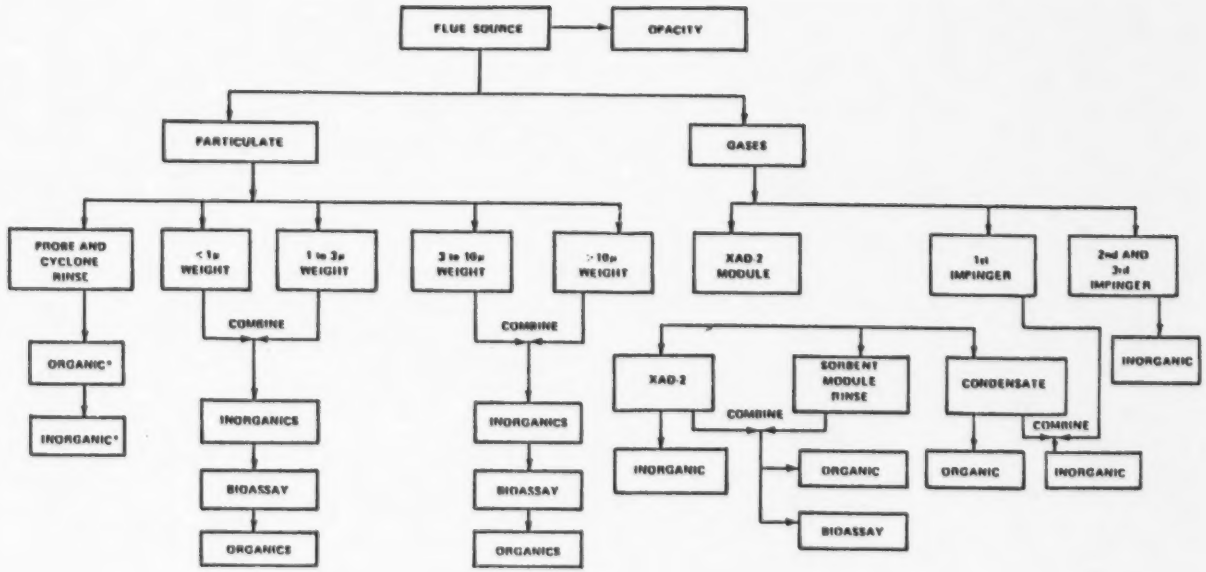


Figure A-4. Flue gas analysis protocol.

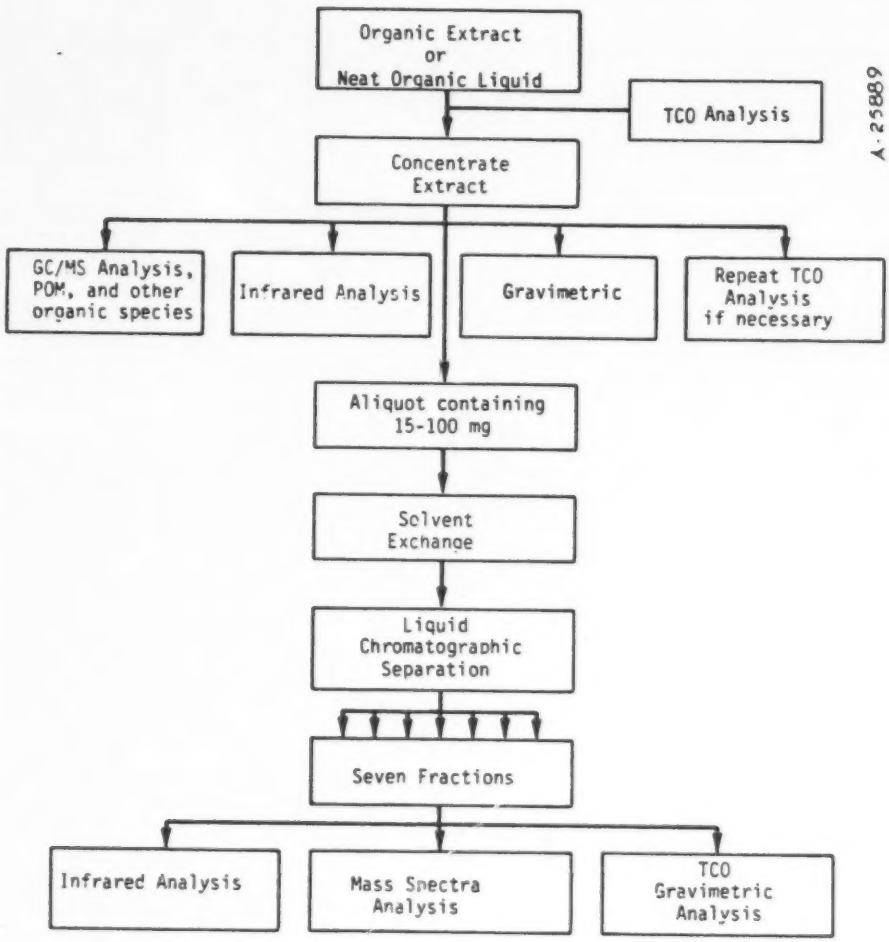


Figure A-5. Organic analysis methodology.

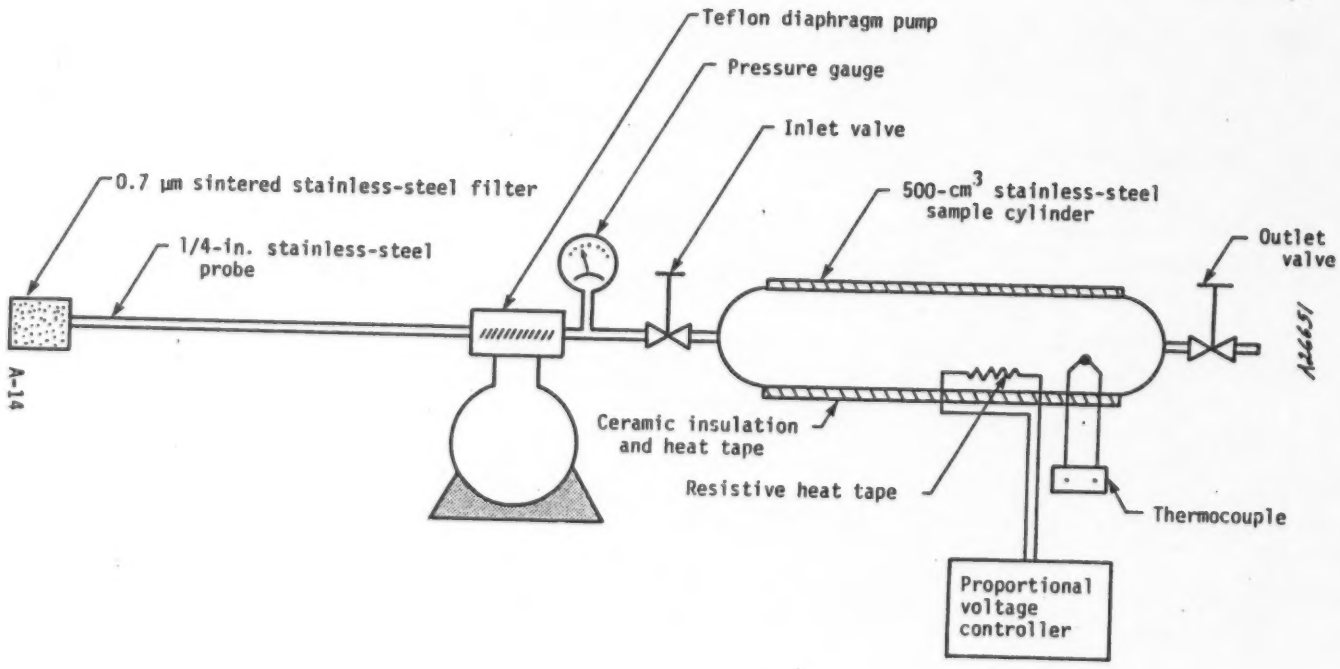


Figure A-6. C_1 to C_6 hydrocarbon sampling system.

steel filter at the probe inlet. The outlet of the probe was directly attached to a diaphragm vacuum pump which was in turn attached to a 500 ml heated stainless steel sampling cylinder. The sampling cylinder was insulated with heat tape powered by a varying voltage controller. The heated jacket kept the sample gas above the dew point to minimize sample loss due to water condensation.

Prior to sampling, the gas cylinder was purged with stack gas for 3 min and then sealed. The trapped flue gas was then analyzed onsite with a Varian Model 3700 gas chromatograph (GC) equipped with a flame ionization detector. Table A-2 lists the design specifications of the Varian GC. A 1.85m (6-ft) long, 0.32-cm (1/8-in.) diameter stainless-steel column packed with Porapak Q 60/80 mesh was used to separate the hydrocarbons into their respective components (C_1 to C_6). The GC was calibrated with repeated injections of a standard gas containing C_1 to C_6 hydrocarbons (each having a concentration of 15 ppm). The chromatographic responses for the standards and the samples were recorded on a Hewlett-Packard Model 3390A reporting integrator.

A.6 N_2O EMISSIONS

Stack gas grab samples were extracted into stainless steel cylinders, similar to those used for C_1 to C_6 hydrocarbon sampling, for laboratory analysis for N_2O. For the analysis, each sample cylinder was externally heated to 120°C (250°F), then a 1-ml sample was withdrawn with a gas-tight syringe for injection into a gas chromatograph. The analytical equipment consisted of a Varian 3700 gas chromatograph equipped with a ^{63}Ni electron capture detector and a 5.5-m (18-ft) stainless-steel column packed for 3.7m (12-ft) with Poropak R 80/100 mesh and 1.8m (6-ft) with Poropak Super Q. The injector temperature was kept at 120°C, the detector at 350°C,

TABLE A-2. GAS CHROMATOGRAPH SPECIFICATIONS

Varian Model 3700 Gas Chromatograph	
Sensitivity	1×10^{-12} A/mV at attenuation 1 and range 10^{-12} A/mV
Zero range	-10^{-11} to 10^{-9} A (reversible with internal switch)
Noise (input capped)	5×10^{-15} A; 0.5 μV peak to peak
Time constant	220 ms on all ranges (approximate is response to 99 percent of peak)
Gas required	Carrier gas (helium), combustion air, fuel gas (hydrogen)

and the column temperature at 39°C. Elution time for N_2O was approximately 7.5 min.

A.7 FUEL AND ASH SAMPLING

Fuel samples were taken from the line running between the fuel tank and the boiler. Ash samples were collected from the boiler and the baghouse after the test.

REFERENCE FOR APPENDIX A

A-1. Lentzen, D.E., et al., "IERL-RTP Procedures Manual: Level 1 Environmental Assessment (Second Edition)," EPA-600/7-78-201, NTIS PB293795, October 1978.

APPENDIX B

TRACE ELEMENT CONCENTRATIONS

The following tables present sample trace element analysis results and trace element discharge stream concentrations. The tables labeled "ppm" represent element analysis results (μg/g or μg/ml) for each sample analyzed. The composition of the coal-water slurry fuel, the bottom ash, the baghouse hopper ash, and all SASS train samples (10 + 3 μm particulate, 1 μm + filter particulate, XAD-2, first impinger, and second and third impingers) are noted.

The tables labeled "concentration" give the calculated flue gas concentration (μg/dscm) of each element corresponding to each SASS train sample, along with the total flue gas concentration (the sum of individual SASS train samples) in the column labeled "flue gas." The tables labeled "mass/heat input" give calculated flue gas concentrations (ng/J) of each element in each SASS train sample, again with the total flue gas concentration (sum of SASS train samples) in the column labeled "flue gas."

Symbols appearing in the tables include:

dscm	Dry standard cubic meter at 1 atm and 20°C
mcg	Microgram
ppm	Part per million by weight
ng/J	Nanogram per Joule
<	Less than

> Greater than

N Element not analyzed

Trace elements having concentrations less than the detectable limit or having a blank value greater than the sample value were given an arbitrary concentration of zero. Values in the form A < x < B were determined by letting elements reported as less than some concentration be represented by a concentration of zero for the low value and the reported (less than) concentration as the high value.

Detectability limits for the various samples were the following:

- Filter -- <0.1 μg/g
- XAD-2 -- <0.01 μg/g
- Impinger and organic module concentrate -- <0.002 μg/ml
- Coal-water slurry -- <0.01 μg/g
- Bottom ash -- <0.2 μg/g
- Baghouse hopper ash -- <0.2 μg/g

At standard conditions (20°C (68°F) and 1 atm), one molecular weight of an ideal gas occupies 24.04ℓ.

Fuel feedrate	kg/s (lb/hr)	0.410 (3,250)
Heat input	MW (million Btu/hr)	8.75 (29.9)
Stack gas flowrate	dscm/s (dscfm)	2.40 (5,120)
Gas collected (SASS)	dscm (dscf)	8.93 (317)
Stack gas molecular weight	dry wet	30.36 28.44

Water in stack gas	(percent)	15.6
O_2	(percent dry)	2.08

PETC

PPM COAL-WATER-SLURRY PPM

ELEMENT	FUEL-CWS	BAGHOUSE ASH	BOTTOM ASH
ALUMINUM	.134E+05	.430E+05	.607E+05
ANTIMONY	.400E+00	.130E+02	.210E+02
ARSENIC	.100E+01	.100E+03	.110E+03
BARIUM	.250E+02	.100E+04	.100E+04
BERYLLIUM	.400E+00	.160E+02	.700E+01
BISMUTH	.300E-01	.800E+00	.300E+01
BORON	.500E+00	.510E+02	.540E+02
BROMINE	.100E+01	.850E+02	.800E+01
CADMIUM	<.400E-01	.400E+01	.900E+01
CALCIUM	.381E+05	.830E+04	.142E+05
CERIUM	.100E+01	.140E+03	.120E+03
CESIUM	.200E+00	.200E+01	.100E+01
CHLORINE	.300E+01	.620E+03	.110E+03
CHROMIUM	.200E+01	.230E+03	.620E+03
COBALT	.100E+01	.190E+03	.210E+02
COPPER	.300E+01	.330E+03	.270E+03
DYSPROSIUM	.100E+00	.600E+01	.800E+01
ERBIUM	.100E+00	.300E+01	.400E+01
EUROPIUM	.700E-01	.400E+01	.100E+01
FLUORINE	.500E+01	.860E+02	.710E+02
GADOLINIUM	.200E+00	.700E+01	.500E+01
GALLIUM	.200E+01	.160E+03	.450E+02
GERMANIUM	.500E+00	.220E+02	.500E+01
HAFNIUM	<.300E+00	.200E+01	.500E+01
HOLMIUM	.100E+00	.400E+01	.500E+01
IODINE	.200E+00	.500E+01	.400E+01
IRON	.700E+03	.361E+05	.435E+05
LANTHANUM	.200E+01	.200E+03	.930E+02
LEAD	.200E+01	.450E+03	.520E+04
LITHIUM	.700E+00	.350E+02	.380E+02
LUTETIUM	.100E-01	.100E+01	.800E+00
MAGNESIUM	>.100E+03	.190E+04	.280E+04
MANGANESE	.200E+01	.500E+03	.500E+03
MERCURY	N.000E+00	N.000E+00	N.000E+00
MOLYBDENUM	.100E+01	.280E+02	.570E+02
NEODYMIUM	.600E+00	.550E+02	.230E+02
NICKEL	.200E+01	.600E+02	.190E+03
NIOBIUM	.500E+00	.510E+02	.350E+02
PHOSPHORUS	.370E+02	.230E+04	.600E+04
POTASSIUM	.103E+05	.250E+04	.500E+04
PRASEODYMIUM	.300E+00	.510E+02	.110E+02
RUBIDIUM	.200E+00	.210E+02	.390E+02
SAMARIUM	.300E+00	.210E+02	.900E+01
SCANDIUM	.300E+00	.320E+02	.470E+02
SELENIUM	.300E+00	.440E+02	.110E+02

PPM	PETC COAL-WATER-SLURRY PPM		
ELEMENT	FUEL-CWS	BAGHOUSE ASH	BOTTOM ASH
SILICON	.692E+05	.630E+05	.104E+06
SILVER	.200E+00	<.200E+01	<.300E+01
SODIUM	.100E+03	.116E+05	.133E+05
STRONTIUM	.340E+02	.300E+03	.300E+03
SULFUR	.440E+04	.550E+04	.550E+04
TANTALUM	.100E+00	.100E+03	.800E+01
TELLURIUM	.200E+00	.600E+00	.100E+01
TERBIUM	.600E-01	.200E+01	.200E+01
THALLIUM	.200E+00	.300E+01	.700E+01
THORIUM	.500E+00	.420E+02	.220E+02
THULIUM	<.200E-01	.300E+00	.200E+00
TIN	.400E-01	.900E+01	.410E+02
TITANIUM	.630E+02	.300E+04	.250E+04
TUNGSTEN	.100E+00	.120E+02	.900E+01
URANIUM	.500E+00	.190E+02	.180E+02
VANADIUM	.300E+01	.200E+04	.200E+04
YTTERBIUM	.100E+00	.600E+01	.400E+01
YTTRIUM	.400E+01	.320E+03	.270E+03
ZINC	.200E+01	.160E+03	.460E+04
ZIRCONIUM	.200E+01	.160E+03	.130E+03

PETC

PPM COAL-WATER-SLURRY

ELEMENT	PPM 10 + 3 MICRON	1U + FILTER	XAD	FIRST IMPINGER
ALUMINUM	.313E+05	.733E+05	.400E+00	.600E-01
ANTIMONY	.110E+02	.180E+02	.000E+00	.900E-02
ARSENIC	.300E+02	.440E+03	.000E+00	.200E-02
BARIUM	.100E+04	.160E+04	.300E+00	.000E+00
BERYLLIUM	.800E+01	.400E+01	.000E+00	.000E+00
BISMUTH	.000E+00	200E+01	.000E+00	.000E+00
BORON	.800E+01	.120E+03	.200E-01	.800E-02
BROMINE	.350E+02	.300E+02	.140E+00	.700E-01
CADMIUM	.600E+01	.300E+01	.000E+00	.000E+00
CALCIUM	.440E+04	.238E+04	.100E+01	.700E+00
CERIUM	.850E+02	.610E+02	.600E+00	.000E+00
CESIUM	.300E+01	.300E+00	.000E+00	.000E+00
CHLORINE	.410E+03	.840E+04	.300E+01	.000E+00
CHROMIUM	.170E+03	.170E+03	.300E+00	.291E+00
COBALT	.140E+02	.270E+03	.400E-01	.480E-01
COPPER	.110E+03	.710E+03	.100E+00	.180E+00
DYSPROSIUM	.900E+01	.300E+01	.000E+00	.000E+00
ERBIUM	.400E+01	.100E+01	.000E+00	.000E+00
EUROPIUM	.200E+01	.100E+01	.000E+00	.000E+00
FLUORINE	.160E+03	.180E+03	.800E+00	.940E+00
GADOLINIUM	.500E+01	.200E+01	.000E+00	.000E+00
GALLIUM	.150E+02	.430E+03	.200E+00	.250E-01
GERMANIUM	.400E+01	.530E+02	.000E+00	.200E-02
HAFNIUM	.400E+01	.800E+00	.000E+00	.000E+00
HOLMIUM	.600E+01	.200E+01	.000E+00	.000E+00
IODINE	.400E+01	.300E+01	.900E-01	.000E+00
IRON	.241E+05	.405E+05	.190E+02	.298E+02
LANTHANUM	.750E+02	.540E+02	.900E+00	.000E+00
LEAD	.150E+03	.770E+02	.300E-01	.000E+00
LITHIUM	.250E+02	740E+02	.100E-01	.000E+00
LUTETIUM	.200E+01	.600E+00	.000E+00	.000E+00
MAGNESIUM	.120E+04	450E+04	.250E+01	.000E+00
MANGANESE	.920E+02	> 530E+03	.170E+00	.898E+00
MERCURY	N.000E+00	N.000E+00	N.000E+00	N.000E+00
MOLYBDENUM	.200E+02	260E+02	.540E+00	.250E+00
NEODYMIUM	.160E+02	.600E+01	.700E-01	.000E+00
NICKEL	.300E+02	480E+03	.400E+00	.990E+00
NIOBIUM	.190E+02	.900E+01	.000E+00	.800E-02
PHOSPHORUS	.160E+04	.280E+04	.480E+00	.100E+00
POTASSIUM	.210E+04	.450E+04	.600E+01	.950E+00
PRASEODYMIUM	.210E+02	.600E+01	.300E+00	.000E+00
RUBIDIUM	.390E+02	.180E+02	.000E+00	.190E-01
SAMARIUM	.170E+02	.500E+01	.000E+00	.000E+00
SCANDIUM	.110E+02	.610E+02	.200E-01	.320E-01
SELENIUM	.150E+02	.290E+02	.600E-01	.196E+00

PETC
PPM COAL-WATER-SLURRY
PPM

ELEMENT	10 + 3 MICRON	1U + FILTER	XAD	FIRST IMPINGER
SILICON	.606E+05	.124E+06	.100E+01	.500E+00
SILVER	<.600E+00	.400E+01	.800E-01	.000E+00
SODIUM	.820E+04	.346E+05	.110E+01	>.680E+01
STRONTIUM	.100E+03	.300E+03	.000E+00	.350E-01
SULFUR	.550E+04	.520E+04	.400E+01	>.930E+01
TANTALUM	.150E+02	.400E+01	.000E+00	.000E+00
TELLURIUM	.100E+01	.400E+00	.000E+00	.000E+00
TERBIUM	.300E+01	.600E+00	.000E+00	.000E+00
THALLIUM	.000E+00	.600E+01	.000E+00	.000E+00
THORIUM	.310E+02	.900E+01	.000E+00	.000E+00
THULIUM	.300E+00	.400E+00	.000E+00	.000E+00
TIN	.100E+01	.600E+01	.000E+00	.300E-01
TITANIUM	.250E+04	.400E+04	.600E+00	.200E-01
TUNGSTEN	.900E+01	.300E+01	.000E+00	.000E+00
URANIUM	.160E+02	.800E+01	.000E+00	.000E+00
VANADIUM	.180E+03	.400E+03	.300E-01	.150E-01
YTTERBIUM	.600E+01	.300E+01	.000E+00	.000E+00
YTTRIUM	.790E+02	.120E+03	.400E-01	.190E-01
ZINC	.880E+02	.730E+02	.700E+00	.350E+00
ZIRCONIUM	.230E+03	.450E+02	.600E+00	.000E+00

PETC
COAL-WATER-SLURRY
MCG/DSCM

CONCENTRATION ELEMENT	10 + 3 MICRON	1U + FILTER	XAD	FIRST IMPINGER	FLUE GAS
ALUMINUM	.144E+06	.154E+06	.583E+01	.111E+02	.297E+06
ANTIMONY	.505E+02	.377E+02	.000E+00	.167E+01	.899E+02
ARSENIC	.138E+03	.923E+03	.000E+00	.371E+00	.106E+04
BARIUM	.459E+04	.335E+04	.437E+01	.000E+00	.795E+04
BERYLLIUM	.367E+02	.839E+01	.000E+00	.000E+00	.451E+02
BISMUTH	.000E+00	.419E+01	.000E+00	.000E+00	.419E+01
BORON	.367E+02	.252E+03	.291E+00	.148E+01	.290E+03
BROMINE	.161E+03	.629E+02	.204E+01	.130E+02	.238E+03
CADMIUM	.275E+02	.629E+01	.000E+00	.000E+00	.338E+02
CALCIUM	.202E+05	.499E+04	.146E+02	.130E+03	.253E+05
CERIUM	.390E+03	.128E+03	.874E+01	.000E+00	.526E+03
CESIUM	.138E+02	.629E+00	.000E+00	.000E+00	.144E+02
CHLORINE	.188E+04	.176E+05	.437E+02	.000E+00	.195E+05
CHROMIUM	.780E+03	.356E+03	.437E+01	.540E+02	.119E+04
COBALT	.642E+02	.566E+03	.583E+00	.890E+01	.640E+03
COPPER	.505E+03	.149E+04	.146E+01	.334E+02	.203E+04
DYSPROSIUM	.413E+02	.629E+01	.000E+00	.000E+00	.476E+02
ERBIUM	.183E+02	.210E+01	.000E+00	.000E+00	.204E+02
EUROPIUM	.917E+01	.210E+01	.000E+00	.000E+00	.113E+02
FLUORINE	.734E+03	.377E+03	.117E+02	.174E+03	.130E+04
GADOLINIUM	.229E+02	.419E+01	.000E+00	.000E+00	.271E+02
GALLIUM	.688E+02	.902E+03	.291E+01	.464E+01	.978E+03
GERMANIUM	.183E+02	.111E+03	.000E+00	.371E+00	.130E+03
HAFNIUM	.183E+02	.168E+01	.000E+00	.000E+00	.200E+02
HOLMIUM	.275E+02	.419E+01	.000E+00	.000E+00	.317E+02
IODINE	.183E+02	.629E+01	.131E+01	.000E+00	.259E+02
IRON	.111E+06	.849E+05	.277E+03	.553E+04	.201E+06
LANTHANUM	.344E+03	.113E+03	.131E+02	.000E+00	.470E+03
LEAD	.688E+03	.161E+03	.437E+00	.000E+00	.850E+03
LITHIUM	.115E+03	.155E+03	.146E+00	.000E+00	.270E+03
LUTETIUM	.917E+01	.126E+01	.000E+00	.000E+00	.104E+02
MAGNESIUM	.550E+04	.944E+04	.364E+02	.000E+00	.150E+05
MANGANESE	.422E+03	> .111E+04	.248E+01	.166E+03	> .170E+04
MERCURY	N .000E+00	N .000E+00	N .000E+00	N .000E+00	.000E+00
MOLYBDENUM	.917E+02	.545E+02	.786E+01	.464E+02	.200E+03
NEODYMIUM	.734E+02	.126E+02	.102E+01	.000E+00	.870E+02
NICKEL	.138E+03	.101E+04	.583E+01	.184E+03	.133E+04
NIOBIUM	.871E+02	.189E+02	.000E+00	.148E+01	.107E+03
PHOSPHORUS	.734E+04	.587E+04	.699E+01	.185E+02	.132E+05
POTASSIUM	.963E+04	.944E+04	.874E+02	.176E+03	.193E+05
PRASEODYMIUM	.963E+02	.126E+02	.437E+01	.000E+00	.113E+03
RUBIDIUM	.179E+03	.377E+02	.000E+00	.352E+01	.220E+03
SAMARIUM	.780E+02	.105E+02	.000E+00	.000E+00	.885E+02
SCANDIUM	.505E+02	.128E+03	.291E+00	.593E+01	.185E+03
SELENIUM	.688E+02	.608E+02	.874E+00	.363E+02	.167E+03

CONCENTRATION	PETC COAL-WATER-SLURRY MCG/DSCM				
ELEMENT	10 + 3 MICRON	1U + FILTER	XAD	FIRST IMPINGER	FLUE GAS
SILICON	.278E+06	.259E+06	.146E+02	.927E+02	.537E+06
SILVER	< .275E+01	.839E+01	.117E+01	.000E+00	.955E+01<X<.123E+02
SODIUM	.376E+05	.725E+05	.160E+02	> .126E+04	> .111E+06
STRONTIUM	.459E+03	.629E+03	.000E+00	.649E+01	.109E+04
SULFUR	.252E+05	.109E+05	.583E+02	> .172E+04	> .379E+05
TANTALUM	.688E+02	.839E+01	.000E+00	.000E+00	.772E+02
TELLURIUM	.459E+01	.839E+00	.000E+00	.000E+00	.543E+01
TERBIUM	.138E+02	.126E+01	.000E+00	.000E+00	.150E+02
THALLIUM	.000E+00	.126E+02	.000E+00	.000E+00	.126E+02
THORIUM	.142E+03	.189E+02	.000E+00	.000E+00	.161E+03
THULIUM	.138E+01	.839E+00	.000E+00	.000E+00	.221E+01
TIN	.459E+01	.126E+02	.000E+00	.556E+01	.227E+02
TITANIUM	.115E+05	.839E+04	.874E+01	.371E+01	.199E+05
TUNGSTEN	.413E+02	.629E+01	.000E+00	.000E+00	.476E+02
URANIUM	.734E+02	.168E+02	.000E+00	.000E+00	.902E+02
VANADIUM	.826E+03	.839E+03	.437E+00	.278E+01	.167E+04
YTTERBIUM	.275E+02	.629E+01	.000E+00	.000E+00	.338E+02
YTTRIUM	.362E+03	.252E+03	.583E+00	.352E+01	.618E+03
ZINC	.404E+03	.153E+03	.102E+02	.649E+02	.632E+03
ZIRCONIUM	.105E+04	.944E+02	.874E+01	.000E+00	.116E+04

PETC

MASS/HEAT INPUT — COAL-WATER-SLURRY — NG/J

ELEMENT	10 + 3 MICRON	1U + FILTER	XAD	FIRST IMPINGER	FLUE GAS
ALUMINUM	.394E+02	.422E+02	.160E-02	.305E-02	.816E+02
ANTIMONY	.138E-01	.104E-01	.000E+00	.458E-03	.247E-01
ARSENIC	.378E-01	.253E+00	.000E+00	.102E-03	.291E+00
BARIUM	.126E+01	.921E+00	.120E-02	.000E+00	.218E+01
BERYLLIUM	.101E-01	.230E-02	.000E+00	.000E+00	.124E-01
BISMUTH	.000E+00	.115E-02	.000E+00	.000E+00	.115E-02
BORON	.101E-01	.691E-01	.800E-04	.407E-03	.796E-01
BROMINE	.441E-01	.173E-01	.560E-03	.356E-02	.655E-01
CADMIUM	.755E-02	.173E-02	.000E+00	.000E+00	.928E-02
CALCIUM	.554E+01	.137E+01	.400E-02	.356E-01	.695E+01
CERIUM	.107E+00	.351E-01	.240E-02	.000E+00	.145E+00
CESIUM	.378E-02	.173E-03	.000E+00	.000E+00	.395E-02
CHLORINE	.516E+00	.483E+01	.120E-01	.000E+00	.536E+01
CHROMIUM	.214E+00	.978E-01	.120E-02	.148E-01	.328E+00
COBALT	.176E-01	.155E+00	.160E-03	.244E-02	.176E+00
COPPER	.138E+00	.409E+00	.400E-03	.916E-02	.557E+00
DYSPROSIUM	.113E-01	.173E-02	.000E+00	.000E+00	.131E-01
ERBIUM	.504E-02	.576E-03	.000E+00	.000E+00	.561E-02
EUROPIUM	.252E-02	.576E-03	.000E+00	.000E+00	.309E-02
FLUORINE	.201E+00	.104E+00	.320E-02	.478E-01	.356E+00
GADOLINIUM	.630E-02	.115E-02	.000E+00	.000E+00	.745E-02
GALLIUM	.189E-01	.247E+00	.800E-03	.127E-02	.268E+00
GERMANIUM	.504E-02	.305E-01	.000E+00	.102E-03	.356E-01
HAFNIUM	.504E-02	.460E-03	.000E+00	.000E+00	.550E-02
HOLMIUM	.755E-02	.115E-02	.000E+00	.000E+00	.871E-02
IODINE	.504E-02	.173E-02	.360E-03	.000E+00	.712E-02
IRON	.303E+02	.233E+02	.760E-01	.152E+01	.552E+02
LANTHANUM	.944E-01	.311E-01	.360E-02	.000E+00	.129E+00
LEAD	.189E+00	.443E-01	.120E-03	.000E+00	.233E+00
LITHIUM	.315E-01	.426E-01	.400E-04	.000E+00	.741E-01
LUTETIUM	.252E-02	.345E-03	.000E+00	.000E+00	.286E-02
MAGNESIUM	.151E+01	.259E+01	.100E-01	.000E+00	.411E+01
MANGANESE	.116E+00	> .305E+00	.680E-03	.457E-01	> .467E+00
MERCURY	N .000E+00	N .000E+00	N .000E+00	N .000E+00	.000E+00
MOLYBDENUM	.252E-01	.150E-01	.216E-02	.127E-01	.550E-01
NEODYMIUM	.201E-01	.345E-02	.280E-03	.000E+00	.239E-01
NICKEL	.378E-01	.276E+00	.160E-02	.504E-01	.366E+00
NIOBIUM	.239E-01	.518E-02	.000E+00	.407E-03	.295E-01
PHOSPHORUS	.201E+01	.161E+01	.192E-02	.509E-02	.363E+01
POTASSIUM	.264E+01	.259E+01	.240E-01	.484E-01	.531E+01
PRASEODYMIUM	.264E-01	.345E-02	.120E-02	.000E+00	.311E-01
RUBIDIUM	.491E-01	.104E-01	.000E+00	.967E-03	.604E-01
SAMARIUM	.214E-01	.288E-02	.000E+00	.000E+00	.243E-01
SCANDIUM	.138E-01	.351E-01	.800E-04	.163E-02	.507E-01
SELENIUM	.189E-01	.167E-01	.240E-03	.998E-02	.458E-01

PETC
COAL-WATER-SLURRY

MASS/HEAT INPUT
NG/J

ELEMENT	10 + 3 MICRON	1U + FILTER	XAD	FIRST IMPINGER	FLUE GAS
SILICON	.763E+02	.712E+02	.400E-02	.254E-01	.148E+03
SILVER	< .755E-03	.230E-02	.320E-03	.000E+00	.262E-02<X<.338E-02
SODIUM	.103E+02	.199E+02	.440E-02	> .346E+00	> .306E+02
STRONTIUM	.126E+00	.173E+00	.000E+00	.178E-02	.300E+00
SULFUR	.692E+01	.299E+01	.160E-01	> .473E+00	> .104E+02
TANTALUM	.189E-01	.230E-02	.000E+00	.000E+00	.212E-01
TELLURIUM	.126E-02	.230E-03	.000E+00	.000E+00	.149E-02
TERBIUM	.378E-02	.345E-03	.000E+00	.000E+00	.412E-02
THALLIUM	.000E+00	.345E-02	.000E+00	.000E+00	.345E-02
THORIUM	.390E-01	.518E-02	.000E+00	.000E+00	.442E-01
THULIUM	.378E-03	.230E-03	.000E+00	.000E+00	.608E-03
TIN	.126E-02	.345E-02	.000E+00	.153E-02	.624E-02
TITANIUM	.315E+01	.230E+01	.240E-02	.102E-02	.545E+01
TUNGSTEN	.113E-01	.173E-02	.000E+00	.000E+00	.131E-01
URANIUM	.201E-01	.460E-02	.000E+00	.000E+00	.247E-01
VANADIUM	.227E+00	.230E+00	.120E-03	.763E-03	.458E+00
YTTERBIUM	.755E-02	.173E-02	.000E+00	.000E+00	.928E-02
YTTRIUM	.995E-01	.691E-01	.160E-03	.967E-03	.170E+00
ZINC	.111E+00	.420E-01	.280E-02	.178E-01	.173E+00
ZIRCONIUM	.290E+00	.259E-01	.240E-02	.000E+00	.318E+00

MASS/HEAT INPUT		PETC COAL-WATER-SLURRY NG/J	
ELEMENT		FUEL-CWS	FLUE GAS
ALUMINUM		.627E+03	.816E+02
ANTIMONY		.187E-01	.247E-01
ARSENIC		.468E-01	.291E+00
BARIUM		.117E+01	.218E+01
BERYLLIUM		.187E-01	.124E-01
BISMUTH		.140E-02	.115E-02
BORON		.234E-01	.796E-01
BROMINE		.468E-01	.655E-01
CADMIUM	<	.187E-02	.928E-02
CALCIUM		.178E+04	.695E+01
CERIUM		.468E-01	.145E+00
CESIUM		.936E-02	.395E-02
CHLORINE		.140E+00	.536E+01
CHROMIUM		.936E-01	.328E+00
COBALT		.468E-01	.176E+00
COPPER		.140E+00	.557E+00
DYSPROSIUM		.468E-02	.131E-01
ERBIUM		.468E-02	.561E-02
EUROPIUM		.328E-02	.309E-02
FLUORINE		.234E+00	.356E+00
GADOLINIUM		.936E-02	.745E-02
GALLIUM		.936E-01	.268E+00
GERMANIUM		.234E-01	.356E-01
HAFNIUM	<	.140E-01	.550E-02
HOLMIUM		.468E-02	.871E-02
IODINE		.936E-02	.712E-02
IRON		.328E+02	.552E+02
LANTHANUM		.936E-01	.129E+00
LEAD		.936E-01	.233E+00
LITHIUM		.328E-01	.741E-01
LUTETIUM		.468E-03	.286E-02
MAGNESIUM	>	.468E+01	.411E+01
MANGANESE		.936E-01	> .467E+00
MERCURY	N	.000E+00	.000E+00
MOLYBDENUM		.468E-01	.550E-01
NEODYMIUM		.281E-01	.239E-01
NICKEL		.936E-01	.366E+00
NIOBIUM		.234E-01	.295E-01
PHOSPHORUS		.173E+01	.363E+01
POTASSIUM		.482E+03	.531E+01
PRASEODYMIUM		.140E-01	.311E-01
RUBIDIUM		.936E-02	.604E-01
SAMARIUM		.140E-01	.243E-01
SCANDIUM		.140E-01	.507E-01
SELENIUM		.140E-01	.458E-01

MASS/HEAT INPUT	PETC COAL-WATER-SLURRY NG/J	
ELEMENT	FUEL-CWS	FLUE GAS
SILICON	.324E+04	.148E+03
SILVER	.936E-02	.262E-02<X<.338E-02
SODIUM	.468E+01	> .306E+02
STRONTIUM	.159E+01	.300E+00
SULFUR	.206E+03	> .104E+02
TANTALUM	.468E-02	.212E-01
TELLURIUM	.936E-02	.149E-02
TERBIUM	.281E-02	.412E-02
THALLIUM	.936E-02	.345E-02
THORIUM	.234E-01	.442E-01
THULIUM	< .936E-03	.608E-03
TIN	.187E-02	.624E-02
TITANIUM	.295E+01	.545E+01
TUNGSTEN	.468E-02	.131E-01
URANIUM	.234E-01	.247E-01
VANADIUM	.140E+00	.458E+00
YTTERBIUM	.468E-02	.928E-02
YTTRIUM	.187E+00	.170E+00
ZINC	.936E-01	.173E+00
ZIRCONIUM	.936E-01	.318E+00